THE STRAIGHT FIELD LINE CONCEPT AND APPLICATIONS

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The straight field line mirror field is a marginal minimum B field with straight nonparallel field lines. This field gives optimal ellipticity, the drift surfaces lie on a magnetic surface, radiofrequency heating of the plasma is predicted to be efficient and MHD stability is provided by the minimum B property. One intended application of the magnetic field configuration is energy production and transmutation of spent nuclear fuel in a fusion-fission machine, where the mirror confined plasma is surrounded by a fission mantle. Reactor safety can be increased with a subcritical fission mantle, and the fission power can exceed the fusion power by as much as a factor of 150 with a reasonable condition for reactor safety margins, and this provides a basis for a compact reactor design. The straight field line mirror concept can also be of interest as a plasma source for synthesis of sophisticated materials.

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1. INTRODUCTION

The Q factor (the energy gain factor) of a mirror machine is primarily limited by ion pitch angle scattering into the loss cone and the end confinement of the electrons. Thermal barriers and recovery of the energy of the particles escaping from the magnetic trap are some means that have been proposed to increase the fusion Q factor, but it is questionable if such measures alone would be sufficient to reach a Q factor required for industrial energy production.

However, there is a possibility to enhance substantially the total energy output if the fusion neutrons, besides the need to reproduce tritium, are used to drive fission reactions in a mantle surrounding the fusion neutron source. Breeding of fissile material such as plutonium, where the produced fissile fuel is intended for energy production in a separate fission reactor, has been discussed over several decades [1,2]. In recent years, the interest has switched more to the possibility to transmute and produce energy from the spent nuclear waste from fission reactors in a fusion-fission machine, designed to maintain a high energy neutron spectrum in the fission mantle surrounding neutron source [3-5]. This switch of interest has been inspired by the ideas developed for accelerator driven systems (ADS), where neutrons are produced in a spallation source from bombardment by a high energy proton beam. With a beam energy around 1 GeV, the peak intensity in of neutrons produced from ADS is around 1.3 MeV, which is one order lower than the 14.1 MeV neutron energy produced in a fusion reaction between deuterium (D) and tritium (T).

The transmutation scenario is more acceptable than the breeding scenario for nuclear nonproliferation. Another concern for the breeding scenario, where fission energy is produced in a critical fast reactor, is reactor safety. The reactor safety of fast reactors can be increased in fusion driven systems by using a subcritical fission mantle. Standard critical fission reactors operate with the effective neutron multiplicity k_{eff} equal to unity. The neutron multiplicity is the ratio of neutrons in the second generation to the neutrons in the preceding generation, and a nuclear accident can occur if k_{eff} for some uncontrolled reason would exceed unity. The fission reactor operation is stabilized around $k_{eff}=1$ by the action of delayed neutrons. The risk for a nuclear accident is pronounced in critical fast reactor which under normal conditions operate with $k_{eff}=1$ and which are cooled by liquid sodium or liquid lead-Bismuth, since a hazardous event could be initiated for instance by a sudden loss of coolant (tube rupture) or of coolant flow (flow blockade). Another reactor safety drawback for fast reactors is that plutonium and americium has a lower fraction of delayed neutrons compared to uranium. In driven systems, sufficient margins for reactor safety is expected if $k_{eff}=0.96$ or lower. If the neutron source is turned off, the energy production in the fission mantle decays, enabling a control of the power output. This increases reactor safety.

In subcritical systems driven by fusion neutrons, the fission power exceeds by a large factor the power output from the fusion neutrons. As high value of the effective neutron multiplication factor k_{eff} as possible is desirable to optimize power production, while reactor safety is improved by lower values. Sufficient reactor safety can be expected with $k_{eff}=0.96$, and the produced fission power then exceeds the fusion power by the factor [5]

$$P_{fis}/P_{fus} \approx 150. \qquad (1)$$

The possibility for large fission power amplification opens up a broader margin for fusion devices. Compact and simple fusion devices, compared to the requirements of a pure fusion reactor, could be useful as neutron sources for transmutation. A survey of ongoing activities in FDS is found in Ref. [6]. The fission mantle thickness needs to be about 1.1 m to achieve the value $k_{eff}=0.96$ [5], which corresponds to the maximum fission power amplification with reactor safety margins [5,6]. Tokamaks, with their geometrical restrictions associated with the toroidal confinement and an upper limit on the acceptable total power produced, cannot for this reason make full use of the potential fission power amplification, and are limited to $P_{fis}/P_{fus} \approx 25$ or less [4]. The open geometry of mirror machines offers greater flexibility in this respect. A detailed simulation on a mirror based FDS has been carried out for the Gas Dynamic Trap (GDT) device at Novosibirsk [5], where almost all produced power are due to fission reactions.

If the produced fission power exceeds the fusion power by two orders, it is sufficient with an electron temperature around 1 keV for a mirror based energy producing fusion-fission reactor [5,7,8]. This suggest that a single sell mirror, such as the straight field line mirror (SFLM) [9], could be of interest for that purpose. A compact, about 20 m long SFLM with a 50 cm midplane plasma radius, may be adequate for 0.2-1GW continuous electricity power production. The quality of plasma confinement, in particular end confinement of electrons and ions, would be a key parameter for the power balance of an FDS based on the SFLM. Even if the plasma confinement in a particular fusion-fission device would not be sufficient for power production, it could still have interest for industrial transmutation of nuclear waste. An efficient transmutation device would also be highly relevant in connection with nuclear nonproliferation.

A world scale energy production for decades or even centuries, where reactor safety and nuclear nonprofileration issues are addressed, could be arranged with a fleet of light water reactors combined industrial transmutation by a fusion driven neutron source [6].

A sufficiently intense neutron source, capable of delivering an average of about $5\cdot 10^{18}$ neutrons per second, is required for industrial transmutation of the spent nuclear waste from 5 standard light water reactors [6]. For pulsed neutron sources, such as ADS, the repetition frequency needs to be high enough for efficient transmutation.

The confinement properties of the SFLM may also find application in other areas. Plasma deposition is used for material synthesis. A small SFLM (about 2m long with a 5 cm midplane radius) could offer a better control of plasma parameters, such as the ionization degree, ion energy, and deposition rate, compared to what is possible with standard plasma devices in this application area.

2. FISSION POWER AMPLIFICATION

In a diffusion approximation, the neutron density in the reactor volume V obeys the equation

$$\partial N/\partial t + LN = \nu_p N \quad , \quad \mathbf{x}\in V \qquad (2a)$$

$$\Gamma = -D\partial N/\partial n + \alpha N \quad , \quad \mathbf{x}\in S \qquad (2b)$$

where N is the neutron density, D is the diffusion coefficient, $LN = -\nabla\cdot(D\nabla N) + \nu_a N$ defines a self adjoint operator and ν_a and ν_p are collision frequencies for the absorption and production (mainly fission reactions) of neutrons. At the boundary of the reactor core, there is an influx of Γ of neutrons from an external neutron source, where the normal vector is directed inward to the reactor core and α corresponds to neutrons reflected at the boundary. Associated with this problem is the eigenvalue problem

$$Lf_m = \lambda_m \nu_p f_m \ , \quad \mathbf{x}\in V, \qquad (3a)$$

$$0 = -D\partial f_m/\partial n + \alpha f_m \ , \mathbf{x}\in s, \qquad (3b)$$

where the eigenvalues $\lambda_0 < \lambda_1 < \lambda_2 < \ldots$ can be ordered in increasing order. The efficient neutron multiplicity for the reactor core, $k_{eff} = 1/\lambda_0$, is determined by the lowest eigenvalue of the reactor equation (3a) and (3b). For a nearly critical driven reactor, $1 - k_{eff} \ll 1$, the stationary driven neutron density distribution can be expressed in terms of the eigenfunction f_0 corresponding to the lowest eigenvalue of the reactor equation. The produced fission power is

$$P_{fis} \approx \int dV\, N \nu_{fis} \ ,$$

where ν_{fis} is the collision frequency for fission reactions and $E_{fis} \approx 200$ MeV is a representative figure for the fission energy produced in each fission reaction, which is substantially larger than the energy $E_{fus} \approx 17.6$ MeV produced in a single fusion reaction. The ratio of produced fission power to the fusion power associated with the influx of fusion neutrons becomes for a nearly critical driven reactor

$$P_{fis}/P_{fis} \approx M_\Gamma E_{fis}/E_{fus},$$

$$M_\Gamma \approx \frac{1}{1-k_{eff}}\frac{1}{\bar{\nu}-1},$$

where M_Γ represents the number of fission reactions generated by a single incident fusion neutron and $\bar{\nu}$ is the average number of neutrons generated in each fission reaction. For typical fission mantles, the parameter $\bar{\nu}$ is in the range $2.4 < \bar{\nu} < 3.7$. Choosing the representative values $\bar{\nu} \approx 3$ and $k_{eff} \leq 0.96$, we obtain

$$M_\Gamma \leq 12.5,$$

and

$$P_{fis}/P_{fis} \leq 150,$$

where the upper limit is for $k_{eff} = 0.96$.

3. PROPERTIES OF THE SFLM

A minimum B producing field has the drawback of producing a strong ellipticity of the flux tube near the mirrors. The optimal choice which combines MHD stability with the smallest possible ellipticity ought to for this reason be a marginal minimum B field. The unique solution for this vacuum magnetic field reads in the near paraxial approximation [9],

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

where s is the arc length of the magnetic field lines, x_0 and y_0 are Clebsch coordinates and c and B_0 are constants.

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

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

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

$$a^2 = \frac{x^2}{(1+z/c)^2} + \frac{y^2}{(1-z/c)^2},$$

which gives the ellipticity $\varepsilon_{ell}(z) = (\sqrt{R_m} + \sqrt{R_m - 1})^2$, where $R_m(z) = B(z)/B_0$ is the mirror ratio along the z axis. For a mirror ratio of 4, $\varepsilon_{ell} = 13.9$ and this seems acceptable for a mirror reactor.

A check shows that to leading orders $|\nabla s| = 1$ and thus $B = B(s)$, which is a marginal minimum **B** field. From this follows that the guiding center magnetic drift is zero, since $\mathbf{v}_{\perp}\mathbf{B} \propto \quad \ulcorner \; \mathrm{C}\; B(s) = 0.$

This implies that each ion moves back and forth on a single magnetic field line. This also implies that the guiding center values $x_{0,\mathrm{gc}}$ and $y_{0,\mathrm{gc}}$ of the Clebsch coordinates are constants of motion [10]. In the vacuum field, the drift trajectories are simply a straight line portions of the flux surface, with no drift of the guiding centers. To first order in the plasma beta, for any distribution function $F(\varepsilon, \mu, x_{0,\mathrm{gc}}, y_{0,\mathrm{gc}})$ of the four constants of motion, a poloidal drift on the magnetic surface is introduced, but there is still no radial drift component [10]. The SFLM does therefore provide an omnigenous equilibrium, and there is no neoclassical increase of the transport [10].

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

4. AMBIPOLAR ELECTRIC POTENTIAL

It is sufficient to reach an electron temperature around 1 keV in a fusion-fission mirror machine with a strong fission power amplification [5,7,8]. The longitudinal variations of the electric potential are crucial for the electron fluid confinement and the electron temperature. Without a specific heating directly on the electrons, it can be assumed that the electron distribution function is close to a local Maxwellian. This implies that along a flux tube the electron density variations and the electric potential are related by the Boltzman relation

$$e(\phi-\phi_0)/k_B T_e = \ln(n_0/n)$$

where n_0 and ϕ_0 are the plasma density and the electric potential at the midplane. If the impurity content is small, quasi neutrality implies $n_\mathrm{i}= n_\mathrm{e}$, where n_i is the fuel ion density. An ambipolar potential, aimed to increase the electron end confinement, would then increase as the fuel ion density decreases away from the midplane [11]. A stronger ambipolar potential would result with a stronger depletion of fuel ions outside the mirrors. In addition, a wall sheath potential, where local quasi neutrality does not apply in this narrow sheath region, helps to increase the end confinement of the electrons, and most electrons escaping out of the mirror confinement region are reflected back to the confinement region by this wall sheath potential [11].

The electrons are heated by the hotter ions by electron drag. It is assumed that all losses of the electron energy occur outside the mirror region. The electron energy balance is then of the form [11]

$$\frac{dW_{loss}}{dt} \approx \frac{dW_{drag}}{dt} - \eta_{loss} \frac{n_{lc}}{\tau_{tr}} k_B T_e .$$

Here, n_{lc} is the loss cone density, which can be reduced by building up a strong electron plugging potential near the mirrors, $\tau_{tr}=2L/\mathrm{v}_{\mathrm{th,e}}$ is the transit time of the electrons and $2L$ is the length of the confining region. The parameter η_{loss} represents the fraction of the loss cone electrons that escape the confining region and become replaced by an influx of cold electrons to assure quasi neutrality. A typical loss cone electron would transit the confinement region many times before it has lost most of its energy by collision processes outside the mirrors. Thus $\eta_{loss} << 1$, and at moderately high electron temperatures η_{loss} decreases rapidly with T_e. Adding the energy contribution to the electrons from collisions with the hot ions, the model predicts an increased electron temperature if the plug density n^* is sufficiently low [11]

$$\frac{n^*}{n_0} = e^{e\Delta\phi / k_B T_e} < 3.4 \times 10^{-25} \frac{B_1}{B_0} \frac{2Ln_0}{r_{ei}^3} \frac{1}{\tilde{T}_i^2 \eta_{loss}} ,$$

where $r_{ei}= T_e \,/\, T_i$, the temperature is in keV and the density and length are in SI units.

As an illustrative example for a fusion-fission reactor, we assume a reactor scenario with a large difference between the ion and electron temperatures. The parameters T_e=2 keV, T_i = 50 keV, $n_0 = 10^{19}\mathrm{m}^{-3}$, $2L$=20m, n^*/n_0=0.01 and a mirror ratio of 4 corresponds to an increased electron temperature provided

$$1/\eta_{loss} > 6,$$

which indicates that if it takes 6 or more longitudinal bounces for a loss cone electron to loose its energy, an increase of the electron temperature above the assumed value 2 keV would arise. In a fusion-fission reactor, the loss of ion energy to the electrons would then be brought down to acceptable values, and a net power production is possible with strong fission power amplification.

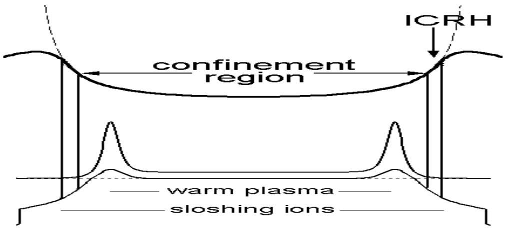

Fig. 2. Variations of the electric potential, density and the magnetic field strength along a flux line.
The lower curves show possible density and electric potential profiles, where a sheath potential near the wall is added. Low energy ions can trap in between the sloshing ion density peaks and provide a warm plasma stabilization. The outer region where $\phi < 0$ near and outside the mirror trap is crucial for confining the electrons. A potential wall sheath can confine a majority of the few loss cone electrons that are able to penetrate the mirror trap

The increased electron temperature in the model relies on a sufficiently strong electrostatic barrier for the electrons, which is related to the possibility to deplete the ion density outside the mirrors. An expanding flux tube outside the mirrors helps in decreasing the plasma density, and this is known to have an MHD stabilizing effect, as demonstrated for the axisymmetric GDT experiment. However, there is the important difference that the MHD stability of the SFLM does not rely on a plasma in the expander region, and the aim for the SFLM is to decrease the plasma density in that region to build up a sufficiently strong ambipolar potential that improves the electron confinement.

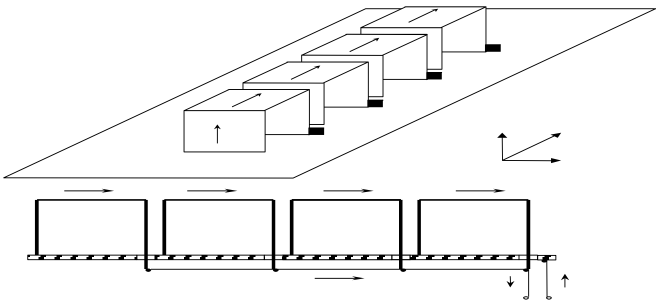

Fig. 3. Strap antenna layout with scheme of electric connection. The antennas can be located outside the fusion region

It could also be essential to avoid onset of longitudinal plasma flow associated with velocity space driven instabilities. Velocity space driven instabilities are suppressed by sloshing ions. A scenario to improve plasma confinement and to produce a sloshing ion population by ion cyclotron resonance heating has been suggested [11-13]. Numerical computations indicate efficient heating of both the deuterium and tritium plasma ions [12,13], and the RF antennas can be localized outside the magnetic mirrors.

Fig. 2 outlines expected profiles for the density and scalar electric potential with the scheme. Fig. 3 shows a strap antenna that is capable of delivering a sufficiently strong heating power.

The end loss is a concern for mirror machines. A stellarator-mirror FDS [7], with a hot tritium sloshing ion distribution trapped in the mirror part, is expected to have better confinement, but the device would be more complicated than the SFLM.

5. CURRENT COILS

There are several alternatives, for instance combinations of circular coils, elliptic coils and curved “Ioffe coils”, to produce the SFLM field. Preliminary result [14] suggest that it is possible to reproduce the SFLM field with reasonable accuracy with a set of circular coils, aimed to reproduce the field on axis, and four curved “Ioffe coils”, where the distance between the Ioffe coils is varied along z to model the gradients of the quadrupolar field.

6. CONCLUSIONS AND DISCUSSIONS

Mirror machines suffer from end losses, and it is hard to achieve a net power output for a pure fusion mirror machine. There is a widened margin to obtain a net power output in a mirror based fusion-fission machine, where a fission mantle surrounds the fusion neutron source. The fission power produced can be more than two orders higher than the fusion power output. Sufficient reactor safety margins are expected if the mantle is designed to operate with k_{eff} =0.96, and the ratio of fission to fusion power is then $P_{fis}/P_{fus} \approx 150$.

It is not possible to make a full use of the potential for a strong fission to fusion power ratio in all types of fusion devices. There is a need to have space for a sufficiently thick (more than 1m) fission mantle in between the plasma confining vessel and the current coils, and holes in the mantle are required for access to the plasma. It is also essential for a reasonably distributed power grid system that each unit does not produce a too strong electric power, i.e. below something like 1 GW. A tokamak are for these reasons restricted to $P_{fis}/P_{fus} \approx 25$ or less [4].

Mirror schemes can make full use of the strong power amplification and operate with k_{eff} =0.96. Mirrors are not limited to pulsed mode operation, and the geometry is almost ideal for a fusion-fission scenario. Simulations for the GDT device have indicated promising possibilities for a mirror based transmutation machine. The axisymmetric geometry of the GDT is beneficial for plasma access, and MHD stability can be achieved with a plasma expander behind the mirror. A net power production is predicted if the electron temperature approaches 1 keV. Ion heating is achieved with neutral beam injection near the midplane, and two separate annular fission mantle regions are located near the sloshing ion turning points. The fusion neutron intensity obtained in the GDT simulations is about one order too low for industrial transmutation of the spent nuclear fuel from five standard fission reactors. Increased fusion power output in GDT is predicted by making the two fusion-fission power production zones longer.

A scenario to base a fusion-fission reactor on the quadrupolar SFLM concept has been outlined. Some of the expected beneficial properties of the SFLM are:

1. MHD stability (minimum B, plasma expander).
2. Optimal ellipticity of the flux tube.
3. Guiding centers move on flux surfaces.
4. Modified thermal barrier reduces end loss.
5. RF heating with high efficiency.
6. Continuous operation possible.
7. Sloshing ion stabilization.
8. Radial transport barrier.

In Gamma 10, a radial transport barrier and increased electron temperature has been produced by shear poloidal **E**×**B** rotation, which in a mirror can be arranged by potential plates of electron cyclotron heating [15]. In the SFLM concept, the electron temperature is expected to rise if the contact is reduced between the plasma confinement region and the region outside the mirrors, i.e. if the plasma density decreases sufficiently much in the external region. In addition, high beta MHD stable plasmas can be achieved, and the geometry allows for convenient solutions for refueling and ash removal. It is possible to place sensitive plasma systems as RF antennas and plasma diagnostics outside the high neutron flux zone. Simple current coils can be used to create the SFLM field.

For the fusion-fission application, the following is essential:

1. Easy plasma access with a fission mantle.
2. Optimal fission power amplification.
3. T_e = 1 keV sufficient.

4. Improved fast reactor safety.
5. A single fission mantle with RF heating.
6. Compact device.

The geometrical simplicity allows for easy adjustment of the size to need for efficiency of transmutation and power production. An uncertainty is the quality of end confinement. Improved plasma confinement is expected for a stellarator-mirror concept, but such a device would be more complicated than the SFLM. Intended size of a power producing SFLM would something like 20 m long with a 50 cm mid plane plasma radius in a 2T midplane magnetic field, which may be adequate for producing an electric power in the range 0.2-1 GW. Such a transmutation machine could be of interest even without power production.

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КОНЦЕПЦИЯ УДЕРЖАНИЯ С ПРЯМЫМИ СИЛОВЫМИ ЛИНИЯМИ МАГНИТНОГО ПОЛЯ И ЕЕ ПРИМЕНЕНИЕ

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Магнитное поле ловушки с прямыми, но непараллельными силовыми линиями имеет минимум в центре. Такое поле обладает минимальной эллиптичностью магнитных поверхностей, дрейфовые поверхности совпадают с магнитными, высокочастотный нагрев может иметь высокую эффективность, и МГД- устойчивость обеспечена минимумом B. Одно из возможных применений такой магнитной конфигурации – производство электроэнергии и трансмутация отработанного ядерного топлива в условиях, когда ловушка находится внутри ядерного реактора. Повышенная безопасность работы реактора обеспечивается его подкритичностью, и коэффициент усиления мощности достигает величины 150 при соблюдении требований безопасности. Концепция удержания с прямыми силовыми линиями магнитного поля может также быть использована в источниках плазмы для синтеза сложных материалов.

КОНЦЕПЦІЯ УТРИМАННЯ З ПРЯМИМИ СИЛОВИМИ ЛІНІЯМИ МАГНІТНОГО ПОЛЯ ТА ЇЇ ЗАСТОСУВАННЯ

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Магнітне поле пастки з прямими, але непаралельними силовими лініями має максимум в центрі. Таке поле має мінімальну еліптичність магнітних поверхонь, дрейфові поверхні співпадають з магнітними, високочастотний нагрів може мати високу ефективність, та МГД- стійкість забезпечена мінімумом B. Одне з можливих застосувань такої магнітної конфігурації – виробництво електроенергії та трансмутація відпрацьованого ядерного палива в умовах, коли пастка знаходиться усередині ядерного реактора. Підвищена безпека роботи реактора забезпечується його підкритичністю, і коефіцієнт підсилення потужності досягає значення 150 з дотриманням вимог безпеки. Концепція утримання з прямими силовими лініями магнітного поля може також бути використаною в плазмових джерелах для синтезу складних матеріалів.