CONCEPTUAL STUDY OF A STRAIGHT FIELD LINE MIRROR HYBRID REACTOR

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A hybrid reactor based on the straight field line mirror (SFLM) with magnetic expanders at the ends is proposed as a compact device for transmutation of nuclear waste and power production. Compared to a fusion reactor, plasma confinement demands can be relaxed if there is a strong energy multiplication by the fission reactions, i.e. $Q_r=P_{fission}/P_{fusion}>>1$. The values of Q_r is primarily restricted by fission reactor safety requirements. For the SFLM, computations suggest that values of Q_r ranging up to 150 are consistent with reactor safety. In a mirror hybrid device with Q_r >100, the lower bound on the electron temperature for power production can then be estimated to be around 400 eV, which may be achievable for a mirror machine. The SFLM with its quadrupolar stabilizing fields does not rely on plasma flow into the expanders for MHD stability, and a scenario with plasma density depletion in the expanders is a possibility to increase the electron temperature. Efficient power production is predicted with a fusion Q = 0.15 and an electron temperature around 500 eV. A fusion power of 10 MW could then be amplified to 1.5 GW fission power in a compact 25 m long hybrid mirror machine. Beneficial features are that all sensitive equipment can be located outside the neutron rich region and a steady state power production seems possible. Self circulation of the lead coolant, which is useful for heat removal if coolant pumps cease to operate, could be arranged by orienting the magnetic axis vertically. Results from studies on plasma equilibrium and stability, coil designing, RF heating and neutron computations are presented.
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1. INTRODUCTION

It is well known that collision losses in a mirror trap seriously limits the Q factor (the fusion energy gain factor). For instance, early Fokker-Planck calculations [1] for the 2XIIB quadrupolar single cell mirror machine predicted Q values no larger than 0.6 for moderate values of the mirror ratio (R_m=3), where axial loss by pitch angle scattering has a key responsibility for the limits. Somewhat higher Q factors may be achieved with alpha particle heating, recovery of the energy of the escaping particles, or by developing more sophisticated mirror confinement schemes such as the tandem mirror or multi mirror traps. Most such attempts (the high density GOL3 multi mirror trap is one exception) have however resulted in predictions for the Q factor below the requirements for a fusion reactor.

Another possibility is to use a low Q mirror machine a hybrid reactor scenario where most of the produced energy comes from fission reactions in a mantle surrounding the fusion neutron source [2-4]. In hybrids, the fusion device delivers a comparatively low fusion power output, and a "semi-poor" plasma confinement could be sufficient for power production if the fission reactions produce a strong energy multiplication Q_r, i.e. the ratio of fission to fusion power. The energy multiplication factor is preliminary restricted by reactor safety and is dependent on hybrid reactor geometry, design of fission mantle etc. A purpose of our studies is to consider mirror machine parameters [5] far from the requirements of a fusion reactor with Q_r > 100. Power production is then a possibility even with a fusion Q factor as low as $Q \approx 0.15$. In mirror machines with a plasma power drain dominated by electron drag, $Q \approx 0.15$ may be achieved with an electron temperature as low as T_e = 500 eV, which seems to be within possible ranges for mirrors [5].

The weak point of mirror hybrids is the plasma confinement quality, in particular the end loss and the associated low electron temperature. Progress in recent years made at the Gamma10 device at Tsukuba [6] and at the Gas Dynamic Trap (GDT) device at Novosibirsk [7] suggests the possibility to achieve a sufficiently high electron temperature for a mirror hybrid.

Compared to other fusion devices, the major advantage of a tokamak hybrid is the plasma confinement quality [8,9]. However, tokamaks suffer from repeated saw teeth events and the need to drive a toroidal current, making steady state power production problematic or even impossible, and a large fraction of the fusion neutrons could not generate fission reactions as a consequence of the holes needed for diagnostics, power feed etc. Tokamak hybrid studies typically consider fusion Q factors in the range 1-2, while an order of magnitude lower Q factors is consistent with power production in a mirror machine. Higher fission to fusion energy multiplication are suitable for mirror machines, more compact designs are possible and steady state operation is not challenged by the need to drive a toroidal current.

A hybrid reactor scenario has been studied for the GDT device [10]. A success of the axisymmetric GDT is the demonstration of interchange stability by the plasma flow through the magnetic throats into the magnetic flux expanders. An uncertainty is whether the plasma in the expanders would prevent rising the electron temperature to values sufficient for a power producing hybrid reactor. In the non-axisymmetric SFLM concept, interchange stability is provided by quadrupolar fields, and plasma in the expanders are not required for MHD stability [11]. Thermal coupling between the confinement and the expander regions is reduced with a plasma density depleted in the expanders. Wide expanders beyond the confinement region are also beneficial for taking care of the power associated with plasma loss.

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 [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].

The transmutation scenario is more acceptable than the breeding scenario for nuclear nonproliferation. Another concern for the breeding scenario, if the fission power would be produced in some separate critical fast reactor, is the reactor safety. Proposals for critical fast reactors aimed to burn spent nuclear from light water reactors are launched within generation IV program for new fission reactors, but there are strong concerns about their reactor safety, in particular when the goal is to burn minor actinides. A fusion hybrid rector seems as a realistic option for more safe burning of the spent nuclear fuel [3-5, 8-9]. In the SFLM proposal, sufficient margins for reactor safety is expected with a neutron multiplicity k_{eff} =0.97 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.

2. REACTOR GEOMETRY

Fig. 1 shows a cross section of the reactor geometry. A plasma with 40 cm radius is confined inside a vacuum tube (radius 90 cm and length 25 m). Located radially outside the vacuum chamber are the first wall (3 cm wide), a blanket with a buffer (15 cm), the fission reactor core with fission fuel and liquid lead bismuth eutectic coolant, core expansion zone, neutron radial reflector (60 cm wide) and a tritium reproduction zone [12].

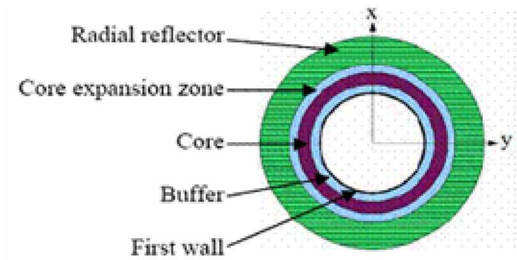

Fig. 1. Cross section showing the vacuum chamber and elements of the fission reactor core

For the nuclear waste burning application, the fuel consists mainly of plutonium and minor actinide isotopes. To avoid generation of minor actinide isotopes, the U238 isotope is (apart from very small amounts) not present in the blanket, and as a result the Doppler broadening (which is of vital importance for the reactor safety of fast reactors without an external neutron source) is almost negligible. The blanket and vacuum region is surrounded by superconducting coils, with a smallest inner radius of 220 cm, compare Fig. 2.

If the plasma would be heated by neutral beams injected near the mid plane as in the GDT hybrid reactor study [10], the reactor would split into two separate parts around the sloshing ions peaks. To avoid this, we here consider ion cyclotron heating with the RF antennas and their power feed located in the high field region, where the neutron flux is low. The ends of the confinement region could be used for diagnostic purposes, refueling, ash removal etc, and the geometry is selected to avoid holes in the fission mantle. The geometry and the minimization of holes in the fission core imply that almost all (99.6%) of the fusion neutrons contribute to fission. As a comparison, simulations for the tokamak FTWR hybrid reactor has shown that only about 39% of the fusion neutrons contribute to fission in that case [9].

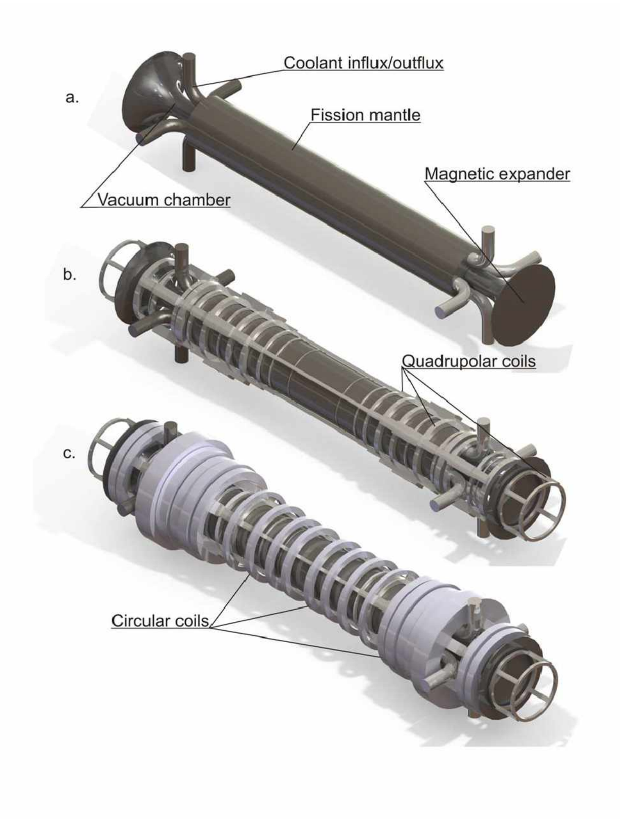

Fig. 2. Coils for an SFLM mirror hybrid machine; chamber stripped from coils (a), quadrupolar coils (b) and entire coil set (c)

3. RF HEATING

RF heating with fundamental ion cyclotron resonance heating is predicted to provide efficient heating on minority deuterium ions with good coupling between the antenna and the plasma [13]. Tritium ions can be heated with second harmonic heating [14]. The RF frequencies are matched to cyclotron resonance conditions at a magnetic field strength about half the maximum field strength, corresponding to locations of sloshing ion density peaks. The antennas for deuterium and tritium heating can be located at opposite ends of the mirror machine.

Geometrically, the RF heating option has the advantage that no holes (except at the longitudinal ends of the confinement region) are introduced in the fission mantle. Neutral beam heating with injection at the midplane could be an alternative heating scheme, but that would be split the fission reactor into two separated parts as a result of the holes required for the beam system.

4. NEUTRON COMPUTATIONS

The geometry and materials in the fission mantle is designed to have an initial neutron multiplicity of k_{eff} = 0.97. This number is selected with the expectation that the reactor would remain in a subcritical state even in "worst case scenarios" [12]. This has been confirmed by detailed Monte Carlo simulations modeling scenarios with loss of coolants as well as partial boiling of the coolants. The worst case found in the computations correspond to the latter scenario, and in all cases studied, the increase in k_{eff} is below 2%, which suggests that a blanket design with k_{eff} = 0.97 initially would provide the reactor in a subcritical state even for a "worst case" accident [12].

The buffer reduces the neutron load on the stainless steel first wall. For the 1.5 GW thermal power case, the 200 dpa limit is predicted to correspond to more than 30 years [12], with 311 days of steady state operation at fixed power each year.

The fuel is slowly burned out, resulting in a lowered k_{eff}. In the 1.5 GW thermal case, k_{eff} decreases to about 0.95 in a one year operation. The energy multiplication at the beginning of the cycle is Q_r = 147 (with k_{eff} =0.97) and is reduced at the end of the cycle by about 40% in a scenario where control rods or burning absorbers are not used to maintain the core at a constant k_{eff}. A constant power output has in such a case to be maintained by increasing the neutron intensity from the fusion neutron source.

The blanket is designed for tritium reproduction. The computed tritium reproduction ratio is 1.8 in one years power cycle [12]. Neutron heat load on the superconducting coils has not been calculated yet, but it is expected that this can be made tolerable, since there are empty spatial locations within the blanket which could be used to further increase the neutron shielding.

The neutron computations have been carried out for a system with a horizontal magnetic axis. A vertical orientation of the magnetic axis could be a better arrangement to assure self circulation by the liquid lead-bismuth coolant in cases where the coolant pumps for some reasons would cease to operate, and to avoid a collapse of the reactor by melting of the reactor core. Even if the neutron source is turned off, self circulation is then required to provide adequate cooling of the residual heat. Neutron studies with a vertical orientation of the magnetic axis are under way.

5. COIL DESIGNING

To first order in plasma β and in a long-thin approximation, the SFLM field is

$$\mathbf{B} \approx (1-\frac{\beta}{2})\mathbf{B}_v \ , \quad (1)$$

where $\beta(\mathbf{x}) = 2\mu_0 P_\perp / B_v^2$ and the vacuum field is

$$\frac{\mathbf{B}_v}{B_0} = \frac{\nabla s}{1-s^2/c^2} \ , \quad (2)$$

where B_0 and c are constants and the arc length of a field line in the long-thin approximation is given by

$$s = z + \frac{x^2/2c}{1+z/c} - \frac{y^2/2c}{1-z/c} . \quad (3)$$

The vacuum field lines correspond to straight nonparallel lines (thus zero curvature) with focal lines at $z = \pm c$. The magnetic drifts are zero in the vacuum field, but an azimuthal drift is present at finite beta, and there also a possibility to arrange a shear radial rotation (which has a positive influence on confinement [6,7]) by radial control plates in the expanders outside the confinement region.

The coil design has to address the wide spatial regions required for the vacuum chamber and the fission reactor core, and the spatial variations of the confining quadrupolar magnetic field. A detailed recent study has demonstrated a coil design with a mirror ratio of 4 for the confinement region, see Fig. 2, with large expanders beyond the confinement region. The coil computations take into account the average minimum B stability criterion. Analysis of the pressure weighted flutes are in progress.

The field generated by coils can be arranged to approach the SFLM field in most of the confinement region. The coil computations also provide "trumpet-like" expanders on each side of the confinement region, as shown in Fig. 2.

6. POWER PRODUCTION ESTIMATES

Some indicate numbers on power production are given for a 1.5 GW thermal case, where most of the power is produced by fission reactions and the energy multiplication is high (Q_r ≈ 100). If we first assume a thermal-to-electric conversion efficiency of 40%, this would correspond to at least 500 MW net electric power production [12]. This may be achieved with a fusion Q as low as Q = 0.15 (an electron temperature of 500 eV would be sufficient for this if the power loss is dominated by electron drag).

Using similar estimates as in the FTWR tokamak simulations for power requirements on pumping coolants etc, results in somewhat less net electric power production, i.e. 450 MW as an average over a cycle with Q=0.15. We need to obtain more precise numbers on the power required to pump the coolants to present more precise estimates for the power production. Self circulation, in particular for a vertical system, is a mean to reduce the power required for the pumping. Such studies are planned for the near future.

An electron temperature around 500 eV, although dramatically lower than that required for a fusion device, is still a challenge for mirror machines, and is connected with the Q factor and the possibilities to reach power production in a hybrid mirror machine. Experiments in Gamma10 and GDT have shown that radial shear rotation can increase the electron temperature [6,7]. The electron temperature also increases with the heating power in the GDT experiments. Density depletion in the expanders may reduce thermal coupling between the confinement region and the expander regions, as briefly analyzed in [5], but deepened studies are required to obtain more reliable predictions on the critical issue of a sufficiently high electron temperature.

The end loss is a concern for mirror machines. A stellarator-mirror FDS [15], 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.

7. SUMMARY 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 fission-fusion 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 in a mirror hybrid reactor.

A commercial reactor in the GW regime has to operate in steady state (for a year or longer). The open geometry of mirror machines is well suited for a steady state hybrid reactor, since a high energy multiplication by fission reactions are possible with reactor safety demands satisfied. Sufficient space is available between the vacuum chamber and the magnetic coils to introduce a buffer (for protection of the first wall neutron loading), fission fuel, neutron reflectors and tritium reproduction zones etc. Plasma heating in ion cyclotron range of frequencies have been considered for the SFLM studies, and a beneficial feature is that this choice of heating does not split the fission reactor core into two separate parts. Monte Carlo simulations predict that the reactor remains subcritical in reactor safety events (loss and boiling of coolants). Load associated with longitudinal plasma loss could be taken care of with large expanders.

Plasma stability is a threat for the efficiency of the system. Large scale plasma activity is not foreseen with an average minimum B field. The warm plasma trapped in between the sloshing ion peaks would have a positive influence on loss cone instabilities, and the axial flow associated with the drift cyclotron loss cone instability is expected to be consistent with a sufficient density depletion in the expander for an increase of the electron temperature [5,16]. Gradient driven instabilities, more localized instabilities and neoclassical effects would have a negative influence on plasma confinement. However, although such effects can be critical for a fusion reactor, the energy confinement time demands of a hybrid reactor may be reduced by two orders, and a “semi-poor” confinement is therefore adequate in the hybrid case, making the hybrid less vulnerable to small scale plasma activity.

The electron temperature is a critical parameter. Thermal coupling between the confinement region and the expanders is reduced with a density depletion in the expanders. Means to achieve an electron temperature around 500 eV, which could be sufficient for power production in a mirror hybrid device, are adressed, but a deepened analysis of the electron temperature physics is required for reliable predictions. Possibility for power production in a mirror hybrid is predicted with a fusion Q as low as 0.15, which is one order lower than predicted critical Q factors of tokamak hybrids.

Sufficient reactor safety margins are expected if the mantle is designed to operate with k_{eff} =0.97, 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. Mirror schemes can make full use of the strong power amplification and operate with a high value of k_{eff}. Simulations for the GDT device have indicated promising possibilities for a mirror based transmutation machine, but a higher electron temperature than so far achieved experimentally is required for a power production.

Some of the expected beneficial properties of the SFLM are high beta plasma stability (by minimum B, plasma expander and sloshing ions), optimal ellipticity of the flux tube, omnigenuity, RF heating with high efficiency and steady state operation.

Shear poloidal $\mathbf{E}\times\mathbf{B}$ rotation, which has a beneficial effect on confinement [6,7], can in the SFLM mirror be arranged by potential plates in the expanders. 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 expander region. The mirror 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. Current coil designing has been carried.

For the fusion-fission application, the following is essential: Easy plasma access with a fission mantle, high energy multiplication by fission, low T_e sufficient for power production, improved fast reactor safety with a driven system, a single fission mantle with RF heating, more than 30 years 200 dpa time limit and an SFLM hybrid would be a compact device. 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 hybrid would be a 25 m long device with a 40 cm mid plane plasma radius, adequate for producing a thermal power of 1.5 GW.

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КОНЦЕПТУАЛЬНОЕ ИССЛЕДОВАНИЕ ГИБРИДНОГО РЕАКТОРА НА ОСНОВЕ ОТКРЫТОЙ ЛОВУШКИ С ПРЯМЫМИ СИЛОВЫМИ ЛИНИЯМИ

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Гибридный реактор на основе магнитной ловушки с прямыми силовыми линиями и магнитными расширителями на концах предлагается использовать как компактное устройство для трансмутации ядерных отходов и производства энергии. По сравнению с термоядерным реактором, требования к удержанию плазмы могут быть понижены, если есть значительное умножение выходной мощности за счет ядерных реакций деления, т.е. $Q_r=P_{fission}/P_{fusion}$>>1. Значения Q_r, в первую очередь, ограничены требованиями к безопасности реакторов. Расчеты показывают, что значения Q_r вплоть до 150 соответствуют таким требованиям. В плазме открытой ловушки гибридного реактора с Q_r> 100 нижняя граница температуры электронов, при которой возможно производство электроэнергии, составляет по оценкам около 400 эВ, что может быть достигнуто в открытой ловушке. Для ловушки с прямыми силовыми линиями, с ее стабилизирующими квадрупольными полями, не столь важна стабилизация МГД-неустойчивостей потоком плазмы в расширители. Сценарий с уменьшением плотности плазмы по мере ее ухода в расширители дает возможность увеличения температуры электронов. Эффективное производство электроэнергии ожидается при термоядерном коэффициенте усиления мощности Q = 0.15 и температуре электронов около 500 эВ. Мощность потока термоядерных нейтронов 10 МВт может быть усилена до 1.5 ГВт за счет реакций деления в компактном гибридном реакторе длиной 25 метров. Преимуществом рассмотренной схемы является то, что все чувствительное к нейтронным потокам оборудование может быть расположено за пределами реакторной зоны и, кроме того, возможен непрерывный режим производства энергии. Если устройство сделано вертикальным, то можно создать условия для самопроизвольной циркуляции свинцового теплоносителя, которая может обеспечить отвод тепла в случае, если насосы перестают работать. Представлены результаты исследования равновесия и устойчивости плазмы, выбор катушек магнитного поля, ВЧ-нагрев плазмы и нейтронные расчеты.

КОНЦЕПТУАЛЬНЕ ДОСЛІДЖЕННЯ ГІБРИДНОГО РЕАКТОРА НА ОСНОВІ ВІДКРИТОЇ ПАСТКИ З ПРЯМИМИ СИЛОВИМИ ЛІНІЯМИ

O. Ågren, В.Є. Моісеєнко, K. Noack, A. Hagnestål

Гібридний реактор на основі магнітної пастки з прямими силовими лініями та магнітними розширювачами на кінцях пропонується використовувати як компактний пристрій для трансмутації ядерних відходів та виробництва енергії. У порівнянні з термоядерним реактором, вимоги до утримання плазми можуть бути знижені, якщо є значне посилення вихідної потужності за рахунок ядерних реакцій поділу, тобто $Q_r=P_{fission}/P_{fusion}$>>1. Значення Q_r, в першу чергу, обмежені вимогами до безпеки реакторів. Розрахунки показують, що значення Q_r до 150 відповідають таким вимогам. У плазмі відкритої пастки гібридного реактора з Q_r> 100, нижня межа температури електронів, при якій можливе виробництво електроенергії, складає за оцінками близько 400 еВ, що може бути досягнуто у відкритій пастці. Для пастки з прямими силовими лініями з її стабілізуючими квадрупольними полями не настільки важлива стабілізація МГД-нестійкостей потоком плазми в розширювачі. Сценарій із зменшенням щільності плазми по мірі її відходу в розширювачі дає можливість збільшення температури електронів. Ефективне виробництво електроенергії очікується при термоядерному коефіцієнті посилення потужності Q = 0.15 і температурі електронів близько 500 еВ. Потужність потоку термоядерних нейтронів 10 МВт може бути посилена до 1.5 ГВт за рахунок реакцій поділу в компактному гібридному реакторі довжиною 25 метрів. Перевагою розглянутої схеми є те, що все чутливе до нейтронних потоків обладнання може бути розташоване за межами реакторної зони і, крім того, можливий безперервний режим виробництва енергії. Якщо пристрій зроблено вертикальним, то можна створити умови для вільної циркуляції свинцового теплоносія, яка може забезпечити відведення тепла в разі, якщо насоси перестають працювати. Представлено результати дослідження рівноваги і стійкості плазми, вибір котушок магнітного поля, ВЧ-нагрів плазми і нейтронні розрахунки.