FUSION-FISSION HYBRID REACTOR STUDIES FOR THE STRAIGHT FIELD LINE MIRROR

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A comparatively small mirror fusion hybrid device may be developed for industrial transmutation and energy production from spent nuclear waste. This opportunity ensues from the large fission to fusion energy multiplication ratio, $Q_r = P_{fis}/P_{fus} \leq 150$, in a subcritical fusion device surrounded by a fission mantle with the neutron multiplicity $k_{eff} \approx 0.97$. The geometry of mirror machines is almost perfectly suited for a hybrid reactor application, and the requirements for plasma confinement can be dramatically relaxed in correspondence with a high value of Q_r. Steady state power production in a mirror hybrid seems possible if the electron temperature reaches 500 eV. A moderately low fusion Q factor, the ratio of fusion power to the power necessary to sustain the plasma, could be sufficient, i.e. $Q \approx 0.15$. Theoretical predictions for the straight field line mirror (SFLM) concept are presented, including results from radio frequency heating, neutron Monte Carlo and magnetic coil computations. Means to achieve an electron temperature of 500 eV are briefly discussed. The basic study considers a 25 m long confinement region with 40 cm plasma radius with 10 MW fusion power and a power production of 1.5 GW thermal.

I. INTRODUCTION

Fusion hybrid reactors have the relaxed plasma confinement demands compared to the challenging requirements for a fusion reactor. Hybrids could also provide enhanced reactor safety for fast fission reactors. Fusion hybrids have for a long time been recognized as a mean to find a quicker application of fusion research, see for instance Ref. 1. The majority of early studies had a focus on breeding new nuclear fuel for fission reactors, with an underlying assumption that a safe fission reactor scheme would be at hand for this purpose. Reactor safety of fast reactors with metal coolants is however a challenging problem, and reactor safety seems to require (in particular for minor actinide burners) a driven system with an external neutron source. Today, several hybrid studies are aiming at finding reactor concepts with enhanced reactor safety[2-7]. The need to take care of the spent nuclear waste, preferentially with a net power production, and non-proliferation issues, are motivations for the studies.

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[6] far from the requirements of a fusion reactor with

$$Q_r \geq 100 \tag{1}$$

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[6]. The accessible Q factor of a single cell mirror is too low for a fusion reactor, as verified by Focker-Planck computations[8]. However, F-P computation results[8] support the idea that a hybrid mirror machine could be capable of producing a net electric power if the energy multiplication by the fission reactions is high enough.

The major advantage of a tokamak hybrid is the plasma confinement quality[2,3]. 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. A mirror machine could use a higher fission to fusion energy multiplication, more compact designs are possible and steady state operation is not disturbed by the need to drive a toroidal current.

An important progress in recent years in mirror research is the improved plasma confinement demonstrated experimentally with shear radial $\mathbf{E}\times\mathbf{B}$ rotation. This was first reported for the Gamma10 tandem mirror[9] and later on for the axisymmetric Gas Dynamic Trap (GDT) device[10], where magnetic expanders are important for interchange stability. In GDT, an electron temperature around 250 eV has been measured by

Thompson scattering. The electron temperature is increasing with the input power of the neutral beams, and there is not yet observed any threshold for this increase. Attractive features with the axisymmetric GDT mirror machine are the simple coil configuration, the high mirror ratio, β values of 60% at sloshing ion peaks, omnigenuity and the avoidance of a highly elliptic magnetic surface cross section associated with quadrupolar fields. A concern is the plasma flow into the expanders (which is required for interchange stability). Plasma in the expander enhance thermal coupling with the confinement region and may be a threat to further increase of T_e. In the non-axisymmetric SFLM concept, interchange stability is provided by quadrupolar fields, and plasma in the expanders are not required for MHD stability[6]. Thermal coupling between the confinement and the expander regions is reduced with a plasma density depleted in the expanders.

A brief summary of theoretical findings for SFLM, including basic equilibrium model, radio frequency studies, neutron Monte Carlo simulations and magnetic coil design, will be presented. Reactor safety margins and load on first wall, expanders etc have been calculated. The studies suggest that a power producing device may be possible with a low fusion Q, and the geometry and choice of heating method fit with hybrid reactor demands.

II. HYBRID RECTOR GEOMETRY

A plasma with 40 cm radius is confined inside a vacuum tube (radius 90 cm and length 25 m). The first wall (3 cm wide) and a blanket with a buffer (15 cm wide), 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 are located radially outside the vacuum chamber, as indicated in Fig. 1. 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 mimportance 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.

The plasma losses are expected to be mainly axial, and a sufficiently wide plate area is needed for taking care of the losses. For this reason, flux tube expander regions are located on each side beyond the 25 m long confinement region. With a 10 MW fusion power and Q ≈ 0.15, the expander wall should be capable to handle a power load in the range 60 MW. With an expander tank radii of 4 m, the total "divertor plate" area is more than 100 m^2, which is expected to provide wide margins for the power load on the expander plates.

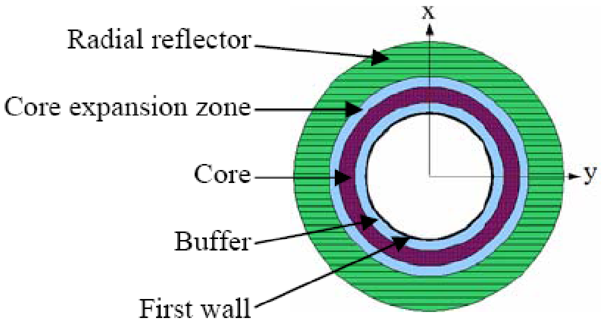

Fig.1 Radial structure of the blanket model.

RF antennas and their power feed can be 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[3,6].

Expander regions with favorable curvature add to interchange stability, which is the key element for stabilization of the axisymmetric GDT device. In the quadrupolar SFLM case, the expanders are not necessary for MHD stability. A purpose of the wide expander is to control the power load on the wall from leaking plasma, and in the SFLM case this can be achieved without a stabilizing plasma flow into the expanders.

The coil design is a complex task as a result of the wide spatial regions required for the vacuum chamber and the fission reactor core, and the spatial variations of the confining quadrupolar magnetic field[6]. A detailed recent study has nevertheless shown that the coil design is possible with a mirror ratio of 4 for the confinement region, see Fig. 2. The coil computations take into account the average minimum B stability criterion. Analysis of the pressure weighted flutes and β limits for ballooning modes are in progress, but have not yet been completed.

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

$$\mathbf{B} \approx (1-\frac{\beta}{2})\mathbf{B}_{\mathrm{v}} \tag{2}$$

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

$$\frac{\mathbf{B}_{\mathrm{v}}}{B_0} = \frac{\nabla s}{1 - s^2/c^2} \tag{3}$$

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

$$s = z + \frac{x^2/2c}{1 + z/c} - \frac{y^2/2c}{1 - z/c} \tag{4}$$

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[9,10]) by radial control plates in the expanders outside the confinement region.

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.

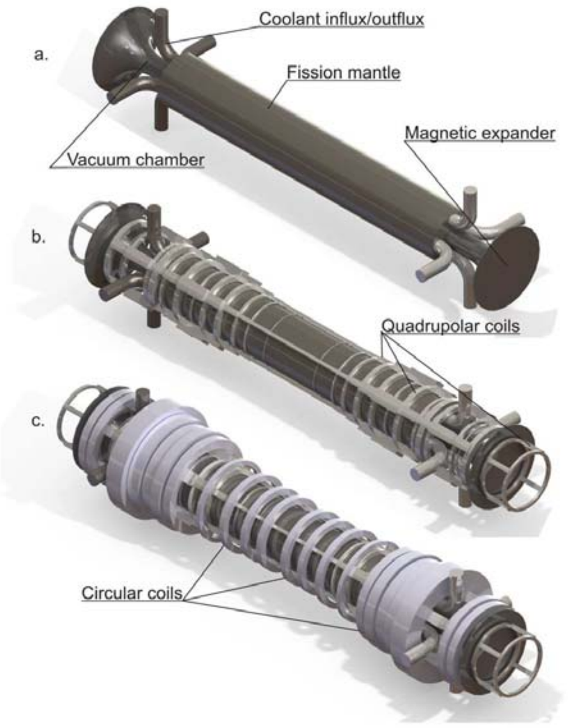

Fig. 2. Coils for an SFLM mirror hybrid machine; chamber stripped from coils (a), quadrupolar coils (b) and entire coil set (c).

III. RF HEATING

RF heating studies with fundamental ion cyclotron resonance heating on minority deuterium ions predict efficient heating with good coupling between the antenna and the plasma[11]. Tritium ions can be heated with second harmonic heating[12]. Antenna frequencies are matched to cyclotron resonance conditions at a magnetic field strength equal 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[6]. 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.

IV. NEUTRON COMPUTATION RESULTS

In Monte Carlo simulations for the neutrons[13], 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" [6,12]. 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[13].

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, with 311 days of steady state operation at fixed power[12] 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[13]. Neutron heat load on the superconducting holes 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 increase the neutron shielding.

V. POWER PRODUCTION ESTIMATES

To estimate the overall power production efficiency, it is vital to get accurate numbers for the power required to heat the plasma and also the power required to cool the superconductors and the fission mantle.

Some indicate numbers 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 ($Q_r \geq 100$). If we first assume a thermal-to-electric conversion efficiency of 40%, this would correspond to at least 500

MW net electric power production[6]. This may be achieved with a fusion Q as low as $Q \approx 0.15$ (an electron temperature of 500 eV would be sufficient for this if the power loss is dominated by electron drag[6]).

The FTWR tokamak simulations predict high power requirements for cooling of the fission mantle. Estimates based on the FTWR simulations for these power requirements transferred to the SFLM scenario give somewhat less optimistic estimates[13], but even in such a case a comparable net electric power production is predicted with a fusion Q of 0.15 in a year cycle of power production. A more precise value for the net power production of the SFLM hybrid requires more detailed analysis of the cooling power etc, which 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 Ref. 6, but deepened studies are required to obtain more reliable predictions on the critical issue of a sufficiently high electron temperature.

VI. SUMMARY AND DISCUSSION

A power producing reactor in the GW regime has preferentially 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) with a tolerable load on the first wall (the 200 dpa limit corresponds to more than 30 full power years). Load associated with longitudinal plasma loss could be taken care of with large expanders beyond the confinement region.

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[6,14]. 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 discussed, 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.

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