The straight field line mirror concept aiming at a hybrid reactor

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INTRODUCTION

The straight field line mirror (SFLM) concept [1-6] is aiming at a steady-state compact fusion neutron source. Besides the possibility for steady state operation for a year or more, the geometry is chosen to avoid high loads on materials and plasma facing components.

Fusion may find its first application in hybrid reactors. A reason is that plasma confinement demands are much less challenging than for a fusion reactor. Power production is mainly from fission reactions in a specifically designed mantle surrounding the fusion neutron source. The role of fusion is merely to control the fission energy production, and a hybrid reactor could be viewed as a "giant power amplifier", where the energy production is proportional to the fusion production and thereby fission can be enabled and controlled by the fusion signal. The fusion part is essential to enhance reactor safety, and the fission production can be switched off by turning off the fusion source. This enhances reactor safety. Further safety enhancement is achieved by arranging a coolant loop where the decay heat after an emergency reactor shut down can be removed by natural circulation.

Our studies predict that only a "semi-poor" plasma confinement (Q_{fusion} =0.15 and T_e = 500 eV could be sufficient) is required for power production. Thus, only modest extrapolation of the already achieved performance in mirror machines is required for power production with the SFLM hybrid reactor concept.

In the SFLM concept, a quadrupolar field provides gross plasma stability. High beta plasmas can be confined in mirror machines. Large expander tanks beyond the confinement distribute axial plasma loss over a large area, and are also aimed to achieve a higher electron temperature.

A brief presentation will be given on basic theory for the SFLM [2] with plasma stability and electron temperature issues [1], RF heating computations with sloshing ion formation [3,4], neutron transport computations with reactor safety margins and material load estimates [5], magnetic coil designs [6] as well as a discussion on the implications of the geometry for possible diagnostics. Reactor safety issues are addressed and a vertical orientation of the device could assist natural coolant circulation. Specific attention is put to a device with a 25 m long confinement region and 40 cm plasma radius in the mid-plane [1]. In an optimal case, with the neutron multiplicity k_{eff} = 0.97 and with a fusion power of only 10-25 MW, such a device may be capable of producing a power of 1.5 GW_{th}.

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). Outside the vacuum chamber is 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 (about 22 cm wide), core expansion zone, neutron radial reflector (60 cm wide) and a tritium reproduction zone [5]. 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 not present in the fuel, 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 210 cm inner radius. Expander tanks with 4m radii play the role of “divertor plates” and have a sufficiently large area to withstand the heat from leaking plasma.

We 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, refuelling, 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 most of the fusion neutrons contribute to fission.

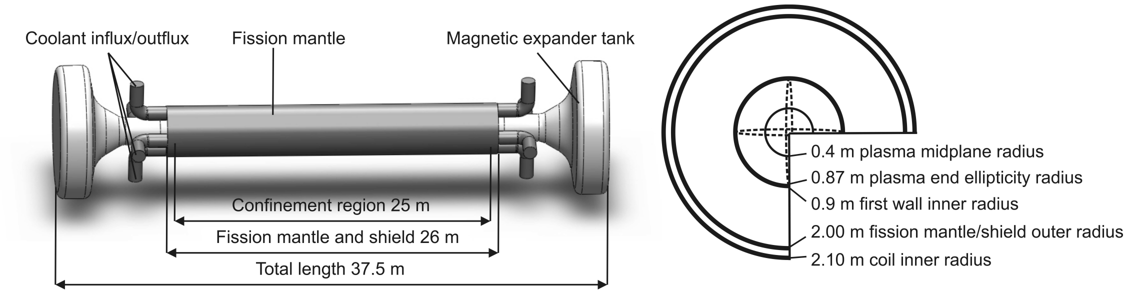

Figure 1. The hybrid reactor without coils, where the coolant outflux/influx, the fission mantle and the vacuum chamber with magnetic expanders are shown.

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

[3]. Tritium ions can be heated with second harmonic heating [4]. 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 scenario has the advantage that no holes (except at the longitudinal ends of the confinement region) are introduced in the fission mantle.

NEUTRON COMPUTATIONS

The geometry and materials in the fission mantle is designed to have an initial neutron multiplicity of k_{eff} = 0.97. This value is selected with the expectation that the reactor would remain in a subcritical state even in "worst case scenarios" [5]. This has been confirmed by detailed Monte Carlo simulations in 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 [5].

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 at the end of a one year cycle with constant power output. The power amplification factor, i.e. the ratio of fission to fusion power is computed, 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 design also provides a tritium breeding ratio above unity. Neutron heat load on the superconducting coils is expected to be within tolerable limits, and empty regions inside the blanket could be used to further increase the neutron shielding.

A vertical orientation of the magnetic axis could be favourable 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, decay heat must be removed, and the design is aimed to make a sufficient self circulation of the coolant for this.

COIL DESIGNING

A design with 3D superconducting coils has been completed with a midplane magnetic field of 1.25 T, a mirror ratio of 4 and large expanders beyond the confinement region [6]. The comparatively cheap superconductor material NbTi is consider for the coils. The quadrupolar field yields an average minimum B field for flute stability.

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. The fission power produced can be more than two orders higher than the fusion power in a mirror hybrid reactor, enabling a lowered confinement demand.

A commercial reactor in the GW regime has to operate in steady state. 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. Material loads appear to be tolerable in the SFLM design. Plasma heating by ion cyclotron heating could be efficient. Monte Carlo simulations predict that the reactor would remain subcritical in reactor safety events (loss and void of coolants).

Large scale plasma activity is not foreseen with an average minimum B field. Further stabilization is provided by the warm plasma trapped in between the sloshing ion peaks. Gradient driven instabilities and neoclassical effects disturb plasma confinement. However, a hybrid reactor has a dramatically lower requirement for plasma confinement than a fusion reactor, and a hybrid is therefore much less vulnerable to small scale plasma activity.

The electron temperature is a critical parameter. Means to achieve an electron temperature around 500 eV, which could be sufficient for power production in a mirror hybrid device, are addressed, and recent mirror experiment suggest this would be possible with increased plasma heating. Possibility for power production in a mirror hybrid is predicted with a fusion Q as low as 0.15. Sufficient reactor safety margins are expected if the mantle is designed to operate with k_{eff} =0.97, and the initial ratio of fission to fusion power is then $P_{fis}/P_{fus} \approx 150$.

References

[1] O. Ågren, V.E. Moiseenko, K. Noack, A. Hagnestål, Fusion Science and Technology. **55**, no. 2T, p. 46 (2010).

[2] O. Ågren and N. Savenko, Phys. Plasmas **12**, ID 022506 (2005)

[3] V.E. Moiseenko, O. Ågren, Phys. Plasmas **12**, ID 102504 (2005).

[4] V.E. Moiseenko, O. Ågren, Phys. Plasmas **14**, ID 022503 (2007).

[5] K. Noack, V.E. Moiseenko, O. Ågren and A. Hagnestål, Ann. Nucl. Energy **38**, p. 578 (2011).

[6] A. Hagnestål, O. Ågren, and V.E. Moiseenko, J. Fusion Energy **30**, 144-156 (2011).