Proceedings of the 2nd IAEA Technical Meeting on First Generation of Fusion Power Plants: Design & Technology

Concept of Multi-function Fusion Reactor

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Abstract: To really use the fusion energy and make the fusion energy as a main energy in the world could need more than 50 years. The construction of ITER starts the real course to realize the peaceful use of the fusion energy. It means the technologies developed in the world are feasible to built fusion facilities or reactors with fusion core plasmas. Based on the technologies nowadays, a concept of multi-function fusion reactor (MFFR) is proposed. MFFR has following functions: fission waste disposal, plutonium 239 breeding from uranium 238, hydrogen producing, tritium producing, components test for fusion reactors, or even electricity power plant demonstration. The preliminary considerations of MFFR are: (a) reasonable configuration and changeable in-vessel function blanket modules, (b) enough flexibility to realize multi-functions separately or at the same time in the facility, (c) suitable plasma core parameters and blanket concept, (d) fully superconducting toroidal and poloidal magnets. Two major types of functional blankets, sub-critical blanket and energy exchange blanket, are defined in MFFR for transmutation of fission waste/fuel and fusion energy transfer. In this paper, the concept of MFFR and the functional blanket based on the results gained in the past years are introduced.

1. Introduction

The ultimate goal of the fusion R&D is energy. The construction of ITER starts the real course to realize the peaceful use of the fusion energy. But to really use the fusion energy and make the fusion energy as a main energy in the world could need more than 50 years. Before the fusion may be used as main energy, to speed up the fusion application is very important. The technologies developed in the world are feasible to built fusion facilities or reactors with fusion core plasmas. Actually, to utilize its large volume neutron source, some of some concepts as immediate step have been studied in the past twenty years, such as the fusion-driven sub-critical system.

Based on the fusion technologies developed in the past years, a concept of multi-function fusion reactor (MFFR) is being proposed in the Institute of Plasma Physics, Chinese Academy of Sciences (ASIPP). The MFFR concept is from the work which has been carried out for earlier use of fusion technologies. The main functions of MFFR, at least, can be: fission waste disposal, plutonium 239 (^{239}Pu) breeding from uranium 238 (^{238}U), hydrogen producing, tritium producing, components test for fusion reactors, or even electricity power plant demonstration. The preliminary considerations of MFFR are: (a) reasonable size and changeable in-vessel function blanket modules, (b) enough flexibility to realize multi-functions separately at the same time in the facility, (c) suitable plasma core parameters and blanket concept, (d) fully superconducting toroidal and poloidal magnets for long pulse or steady-state operation.

2. MFFR Concept

MFFR has a tokamak fusion core with different functional blankets in vessel. The fusion core may produce fusion energy with large volume neutrons. The fusion power can be from hundreds mega watts to several giga watts. The energy density of the functional blankets can be designed around several tens to hundreds mega watts per cubic meter according to the fusion power. The blankets should be changeable remotely during the maintenance according to application requirements, such as the functional blankets of fission waste disposal, ^{239}Pu proliferation from ^{238}U, hydrogen producing, tritium producing, component test for fusion reactors. But, to fulfill the function of fission waste disposal and ^{239}Pu proliferation from ^{238}U, sub-critical blankets have to be adopted for neutron multiplication and transmutation efficiency promotion. The technology and the feasibility for the fusion power plant also can be demonstrated by MFFR. For component test, the full scale in-vessel components of fusion reactors can be installed and tested in MFFR. With some test cells in the cryostat, some structures can also be tested.

2.1 Fusion Core

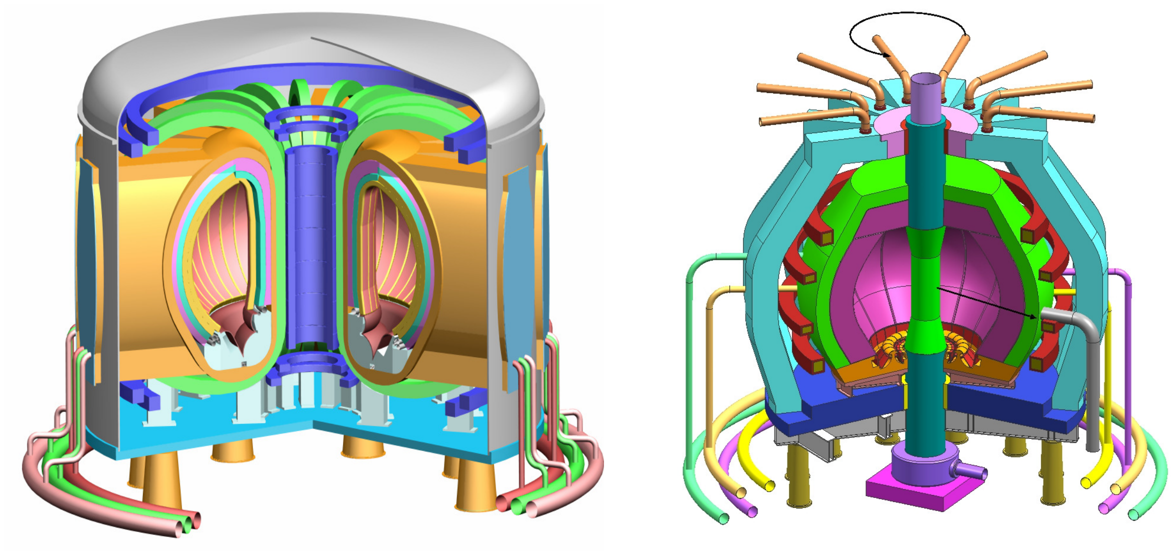
It is expected that the MFFR technologies could be promoted by ITER successful construction and operation. Especially, the technologies of test blanket module for tritium breeding, plasma control, inductively/non-inductively plasmas driven and heating with $Q \geq 5$-10 of deuterium-tritium plasmas are being developed and will be demonstrated during the construction phase and operation phase. The availability and integration of technologies essential for fusion reactors, such as superconducting magnets and remote maintenance are also being developed.

Several reactor concepts based on the up-to-date fusion technology have been designed and assessed by the FDS (Fusion Design Study) Team in ASIPP [1-4, 6-8]. Up to now, two fusion-driven sub-critical systems, the tokamak-based reactor and the spherical tokamak-based compact reactor, have been preliminarily developed for exploiting the possibility of earlier application of fusion energy as volumetric neutron sources. Other two fusion reactor concepts also have been drafted for the fusion electrical generation and the fusion-based hydrogen production reactor.

The tentative plasma parameters of MFFR are selected on the basis of reactor concepts mentioned above and both physics and engineering/technology considerations. The tentative plasma related parameters of MFFR are given in TABLE I [5] for comparison. More details on design optimization of fusion plasma core are being carried out. Both tokamak-based reactor and spherical tokamak-based reactor are options for the fusion core of MFFR. If the technology of the so-called Center Conductor Post (CCP) in the limited space can be developed successfully, the spherical tokamak-based reactor will be more attractive than normal aspect ratio tokamaks for its high ratio of plasma pressure to magnetic pressure β, high plasma current Ip with a modest size device and elimination of thick inboard shield for cryogenic toroidal-field coil. Figure 1 shows the configuration draft of tokamak-based reactor (a) and spherical tokamak-based reactor (b).

TABLE I: THE TENTATIVE PLASMA PARAMETERS OF MFFR

Parameters	MFFR
Fusion power (MW)	2500
Major radius (m)	6
Minor radius (m)	2
Aspect ratio	3
Plasma elongation	1.8
Triangularity	0.6
Plasma current (MA)	15
Toroidal-field on axis (T)	5.93
Safety factor/q_{95}	5
Auxiliary power (MW)	80
Average neutron wall load (MW m^{-2})	2.72
Average surface heat load (MW m^{-2})	0.54



(a) *(b)*

Fig. 1 The configuration draft of MFFR

2.2 Blanket Concepts

Except for the fusion reactor components test module, two major types of functional blankets are defined in MFFR, which are sub-critical blanket and energy exchange blanket. The sub-critical blanket will be mainly used for fission waste transmutation and ^{239}Pu breeding from ^{238}U. While the function of the energy exchange blanket will be transferring the fusion energy from MFFR to produce hydrogen and even to drive turbines for electricity power plant demonstration.

Both type blankets have common function for tritium breeding. The liquid lithium lead breeder blanket is considered as primary option for both of blankets due to their potential attractiveness of economy and safety and relatively mature technology base. Four types of the liquid LiPb blanket concepts [9], including the He/LiPb dual-cooled waste transmutation (DWT) blanket, the He single-cooled LiPb (SLL) tritium breeder blanket, the dual-cooled He/LiPb (DLL) blanket and the high temperature liquid LiPb (HTL) blanket have been proposed and assessed.

2.2.1 Sub-critical Blanket Concept

The sub-critical blanket is designated to transmute the long-lived nuclear wastes from fission power plants and to produce fissile nuclear fuels for feeding fission power plants. It can be He-gas/liquid LiPb dual-cooled high level waste transmutation (DWT) blanket with very attractive advantages, which enables adequate excess neutrons available for breeding fissile fuels, transmuting long-lived fission products and actinides. In addition, there are very low risk of critical accident and less danger to nuclear proliferation comparing to the critical fission systems.

The DWT blanket design has focused on the technology feasibility and concept attractiveness to meet the requirement for tritium sustainability, safety margin and operation economy. A design and its analysis with Carbide heavy nuclide Particle fuel in circulating Liquid LiPb coolant (named DWT–CPL) has been studied for years. Figure 2 shows Reference module of DWT-CPL outboard blanket, and the concave is the first wall (FW) of plasmas. Other concepts such as the DWT blanket with Oxide heavy nuclide Pepper pebble bed fuel in circulating helium-Gas (named DWT–OPG) and with Nitride heavy nuclide Particle fuel in circulating helium-Gas (named DWT–NPG) are also being investigated. Detailed design is introduced in Ref. [6-8].

In the DWT–CPL blanket concept, helium gas was adopted to cool the structures and long-lived fission product (FP) transmutation zones (FP-zones). Actinide (AC) zones (AC-zones) including Minor Actinides (MA) transmutation zones (MA-zones) and Uranium-loaded fissile breeding zones (U-zones) is to be self-cooled by liquid metal (LM) LiPb eutectic with tiny particle of long-lived fuel. U-zones may be replaced by AC-zones if fertile-free concept is considered. Figure 3 shows He-gas/liquid LiPb dual-cooled structure of DWT-CPL blanket in detail. From Fig. 3 it can be seen that by toroidal/radial stiffened plates (tpSP and rpSP) AC-zone is divided into several channels cooled by liquid LiPb. FP-zones in the back area and all structures are cooled by helium gas. Helium gas goes to the 1st channel near the FP-zone and then to FW, through the 2nd channel and all SP into final manifolds. The channels are formed by back plates (BP).

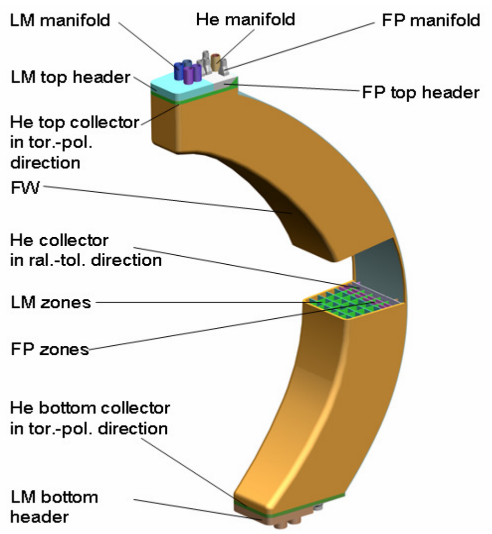


Fig.2 Reference module of DWT-CPL blanket

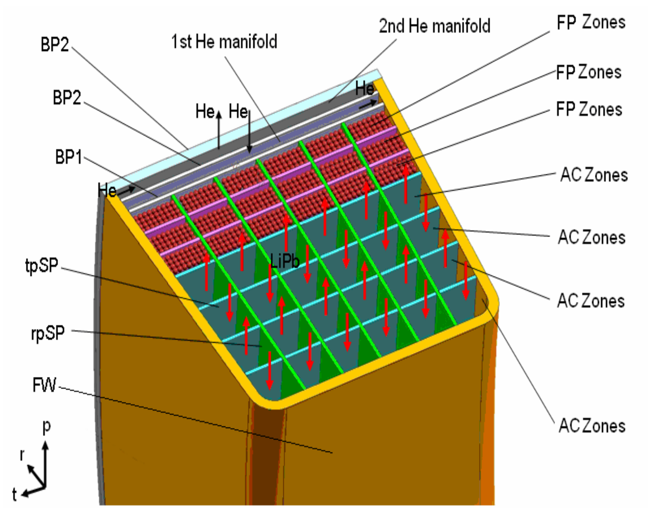


Fig.3 He-gas/liquid LiPb dual-cooled structure of DWT-CPL blanket

Based on the parameters of the tokamak-based MFFR and the DWT blanket concept, the preliminary calculation indicated the initial loaded mass of fission product can be 7 t MA, 48 t Pu, 88 t ^{238}U and several tons of some other fission products, such as cesium, iodine and technetium. The transmuted mass after one year operation could be 0.7 t MA, 6 t Pu and 5 t ^{238}U. Meanwhile about 7 t ^{239}Pu and 15 kg tritium can be produced.

2.2.2 Energy Exchange Blanket Concept

Both the feasibility and attractiveness of technology are of concern to the blanket design for energy exchange blanket concept, which must meet the requirement for tritium self-sufficiency, safety margin, operation economy and environment protection, etc. Two optional concepts of liquid LiPb blankets including the Reduced Activation Ferritic/Martensitic (RAFM) steel-structured He single-cooled LiPb tritium breeder (SLL) blanket, the RAFM steel-structured He-gas/liquid LiPb dual-cooled (DLL) blanket are developed. A high temperature Lithium Lead (HTL) breeder blanket is also proposed and under development.

The DLL blanket consists of self-cooled LiPb breeding zones and helium-cooled structures made of the RAFM steel, e.g. the CLAM (China Low Activation Martensitic) steel [9-10]. The thermal and electrical insulation FCIs (Flow Channel Inserts, e.g. SiCf/SiC composite or other refractory materials) are designed and used inside the LiPb coolant channels to act as both thermal and electrical insulation and keep the temperature of RAFM structure below the maximum allowable temperature. Coating (e.g. Al_2O_3) is considered in the design to reduce tritium permeation and to protect the steel structure against corrosion of LiPb. The DLL blanket concept has the potential to reduce MHD pressure drop and obtain high coolant exit temperature up to 700 °C.

The SLL blanket is a backup option for energy exchange blanket if the critical issues of the DLL blanket, such as MHD effects and FCI technology, could not be solved and validated by testing in ITER. It is designed to use quasi-static LiPb flow instead of fast flow LiPb with similar basic structure, material and auxiliary system of the DLL module. Compared to the DLL blanket concept, SLL blanket concept can be developed fairly easily, but with low thermal efficiency.

Either DLL or SLL blanket is designed as “multi modules” structure, which can reduce the thermal stresses and electromagnetic forces caused by plasma disruption. Figure 4 shows the exploded view of one DLL outboard blanket module in the equatorial zone. The details about this design can be found in Ref. [1, 3 and 9].

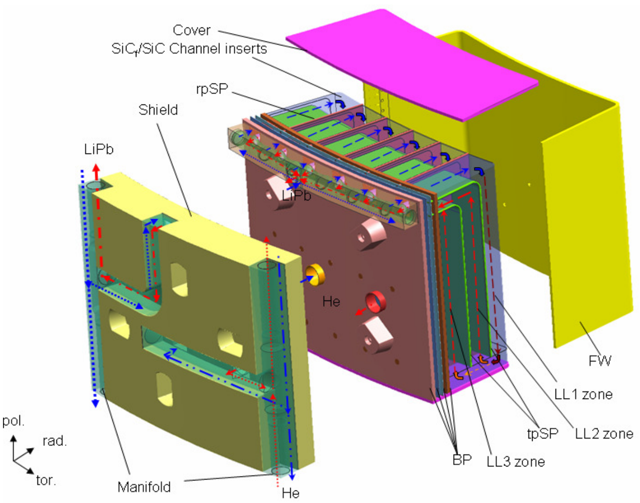
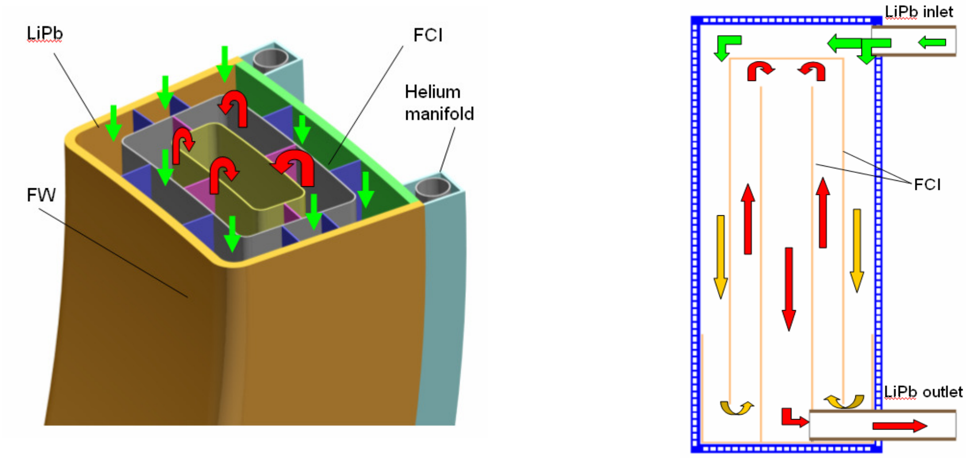


Fig.4 The exploded view of DLL equatorial outboard blanket module

High temperature is attractive for high efficiency production of hydrogen using thermo-chemical Iodine-Sulphur cycles technology and for driving turbine generators. A high temperature Lithium Lead (HTL) breeder blanket [4] which aims to obtain the high temperature heat in the blanket of fusion reactor is being developed. The HTL blanket is designed with the relatively mature and most promising RAFM steel as structural material. A so-called “multilayer flow channel inserts (MFCIs)” with thermal insulating and electricity insulating are proposed in the coolant flow channels. So the temperature gradient of the coolant LiPb can be improved. Some refractory materials with low thermal conductivity and low electricity conductivity can be used as FCI material, such as SiCf/SiC composite. Liquid LiPb can be heated up to the maximum compatible temperature of LiPb and SiCf/SiC composite. Low temperature LiPb flows into the channel, and then meanders through MFCIs. The LiPb temperature exported from the blanket can be higher than 900 °C. To keep the temperature of RAFM structural material below the design limit of 550°C, high pressure helium is used to cool the blanket structures. The details of this design can be found in Ref. [1, 4 and 9]. Schematic layout of blanket structure (a) and LiPb flow channel (b) are shown in figure 5.



(a) *(b)*

Fig.5. Schematic layout of blanket structure and LiPb flow channel

The analyse shows the heat conversion efficiency of the DLL blanket with helium cooling can be up to 47%. If the technology of thermo-chemical Iodine-Sulphur cycles is used and with 850 °C outlet temperature, the efficiency of the hydrogen producing could be 50%.

China Party has proposed the SLL/DLL blanket to be one of two options for ITER TBM. A Dual-Functional Lithium Lead–Test Blanket Module (DFLL–TBM), which is designated to demonstrate the integrated technologies of both He single coolant (SLL) blanket and He–LiPb dual coolant (DLL) blanket, is proposed for test in ITER [9]. The technology R&D is underway in China.

3. Summary

The energy demand of China in the near future will be increased tremendously. To use large volume neutron of fusion earlier, based on the R&D of the up-to-date fusion technology and previous study on the series of reactor concepts, especially expectation of successfully construction and operation of ITER, the concept of MFFR with different functional blankets is proposed. The DFLL–TBM is planned to be tested in ITER. Even though some uncertain in technologies and politics ahead, to start the fusion application study can not be delayed.

Acknowledgment

All work introduced above is the contribution of the FDS team supported by the Ministry of Science and Technology of China, The National Natural Science Foundation of China, the Chinese Academy of Sciences and ASIPP.

References

[1] Y. Wu, the FDS teams, Conceptual design activities of FDS series fusion power plants in China, Fusion Eng. Des. 81(2006) 2713-2718.

[2] Y. Wu, S. Zheng, X. Zhu, W. Wang, H. Wang, S. Liu, Y. Bai, H. Chen, L. Hu, M. Chen, Q. Huang, D. Huang, S. Zhang, J. Li, D. Chu, J. Jiang, Y. Song, FDS Team. Conceptual Design of the Fusion-Driven Subcritical System FDS-I [J], Fusion Eng. Des. 81(2006) 1305-1311.

[3] Y. Wu et al., Conceptual Design study on the fusion power reactor FDS-II, Chinese J. of Nuclear Science and Engineering 1(2005) 76-83.

[4] Chen Hongli, Wu Yican, Bai Yunqing. Study on Thermal-hydraulic New Concept of the High Temperature Liquid Blanket for Hydrogen Production. Chinese Journal of Nuclear Science and Engineering, 2005, 25(4) 374-378.

[5] Technical Basis for the ITER-FEAT Outline Design, G A0 RI 2 00-01-18 R1.0, January 2000. Also see "Summary of the ITER Final Design Report", G A0 FDR 4 01-06-28 R 0.2, July 2001.

[6] Y. Wu, Progress in fusion-driven hybrid system studies in China, Fusion Engineering and Design, 63-64 (2002) 73-80.

[7] Y. Wu, J. Qian and J. Yu, The fusion-driven hybrid system and its material selection, Journal Nuclear Material 307–311 (2002) 1629-1636.

[8] Y. Wu, S. Zheng, X. Zhu, W. Wang, H. Wang and S. Liu et al., Conceptual design of the fusion-driven subcritical system FDS-I, Fusion Engineering and Design, 81 (2006) 1305-1311.

[9] Y. Wu et al, FDS Team. Development of China Liquid Lithium-Lead Blanket and Its Material Technology, presented at the 12th International Conference on Fusion Reactor Materials, Santa Barbara, USA. December 5-9, 2005; to be published in Journal of Nuclear Materials. in Press, doi:10.1016/j.jnucmat.2007.04.031.

[10] Q. Huang, C. Li, Y. Li, Progress in Development of China Low Activation Martensitic Steel for Fusion Application, presented at the 12th International Conference on Fusion Reactor Materials, Santa Barbara, USA. December 5-9, 2005; to be published in Journal of Nuclear Materials. in Press, doi:10.1016/j.jnucmat.2007.03.153.