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Conceptual design of a liquid metal limiter/divertor system for the FFHR-d1

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HIGHLIGHTS

- A new liquid metal divertor named the REVOLVER-D is proposed for the FFHR-d1.
- It consists of molten tin shower jets stabilized by internal flow resistances.
- The molten tin showers are inserted into the ergodic layer as a limiter/divertor.
- Tin is selected by reasons of low vapor pressure, low cost, and high safety.
- The liquid metal pumps and vacuum pumps are installed inside the central solenoid.

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ABSTRACT

A new liquid metal divertor system named the REVOLVER-D (Reactor-oriented Effectively VOLumetric VERtical Divertor) is proposed for the helical fusion reactor FFHR-d1. The REVOLVER-D is composed of molten tin shower jets stabilized by internal flow resistances of wire/tape/chain. These shower jets are inserted into the ergodic layer surrounding the main plasma. Tin is selected as the liquid metal because of its low melting point, low vapor pressure, low material cost, and high safety. The liquid metal pumps, cryopumps, and turbo molecular pumps are installed in the central vacuum vessel connected to the main vacuum vessel via 10 inner ports equipped with maze neutron shields. Central solenoid coils made of high-temperature superconductors are installed inside the central vacuum vessel to shield the pumps from the strong magnetic field. The REVOLVER-D has a good possibility to satisfy important characteristics required for the divertor system in a fusion reactor, that is, high heat load tolerance, high maintainability, sufficient vacuum pump speed, high level of safety, and a small amount of radioactive wastes.

1. Introduction

Conceptual design activity of a helical fusion reactor FFHR-d1 is ongoing [1,2]. In designing the divertor system for FFHR-d1, special emphasis is placed on five issues, that is, high heat load tolerance, high maintainability, sufficient vacuum pump speed, high level of safety, and a small amount of radioactive wastes. To satisfy these requirements, a new concept of limiter/divertor consisting of liquid metal shower jets has been proposed and named REVOLVER-D (Reactor-oriented Effectively VOLumetric VERtical Divertor).

The FFHR-d1 is a heliotron-type fusion reactor, of which the arrangement of superconducting magnetic coils is similar to that in the Large Helical Device (LHD) [3]. The device size is four times larger than the LHD. The major radius of the helical coil center is 15.6 m, the magnetic field strength is >5 T at the plasma center, and the fusion output is ~3 GW [1,2]. The FFHR-d1 is inherently equipped with a helical divertor, as is the LHD [4]. Compared with the conventional poloidal divertor in tokamaks, the helical divertor is characterized by a large plasma-wetted area spreading over both toroidal and poloidal directions. For example, the typical plasma-wetted area in LHD is estimated to be ~2 m^2 [5]. Since the footprint

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of the helical divertor is basically determined by the distribution of magnetic field lines of force, the plasma-wetted area in FFHR-d1 can be estimated as ~2 × 4 × 4–32 m^2, as long as the divertor plates are similarly placed in these two devices. If there is no radiation loss in FFHR-d1 and all of the alpha heating power of 600 MW hits the divertor in steady-state, then the averaged divertor heat flux becomes ~20 MW/m^2. This can be largely reduced by enhancing the radiation loss and realizing “divertor detachment” [6]. However, it will not be as easy as in LHD to control the detachment in the fusion reactor, where only poor measurements and actuators will be available due to the high neutron and γ-ray irradiations. Furthermore, as observed in LHD, the profile of the divertor heat load is not constant. The peak heat load will be at least a few times larger than the averaged heat load [4,7]. Although an attempt to flatten the divertor footprint distribution in the toroidal direction has been examined for FFHR-d1 by configuration optimization using additional coils [8], this attempt is still insufficient. Therefore, in the worst case, where radiation cooling is not sufficient and the plasma attaches to the divertor plates, the peak heat load can exceed more than several tens of MW/m^2 in FFHR-d1. This is not acceptable for conventional solid material divertors. Indeed, the maximum heat load of the water-cooled tungsten monoblock divertor with copper cooling pipes being developed for ITER is limited to 10–20 MW/m^2 [9]. On the other hand, flowing liquid metals can tolerate high heat loads. For instance, in the International Fusion Materials Irradiation Facility (IFMIF), designs call for irradiating a liquid lithium flow with a 1 GW/m^2 deuterium beam. The liquid lithium flow in IFMIF can resist such a high heat load in steady state, since its flow velocity is as fast as 15–20 m/s [10].

There are many proposed designs for utilizing liquid metals in plasma-facing components. The first proposal of liquid metal divertor was made in the design of UWMAK-1 in 1974 [11]. Application of the free surface of liquid lithium or molten salt to the first wall was also proposed in the design of the HYLIFE-I and HYLIFE-II inertial fusion reactors [12]. To keep the molten salt on the ceiling, the Kunugi-Sagara type Free surface (KSF) wall was proposed in the FFHR design, where micro grooves were made on the first wall to use the capillary force to withstand the gravitational force [13]. In the ARIES-RS design, the Convective Liquid Flow First-wall concept (CLiFF) was proposed after intensive studies of APEX [14]. The CLiFF consists of a first-wall covered with fast flowing liquid metal and a divertor with fast droplet flow. In experimental studies, lithium has been applied in many devices, since the lithium coated vacuum vessel wall is effective for hydrogen recycling reduction. For instance, the Capillary Porous System (CPS), where molten lithium oozes from a molybdenum mesh, has been successfully applied to T-11 M [15], FTU [16], and TJ-2 [17]. A good energy confinement property has been demonstrated in the Lithium Tokamak eXperiment (LTX) equipped with a large area liquid lithium wall [18]. The Liquid Lithium Divertor (LLD), where the divertor is composed of porous molybdenum plates including lithium was also applied in NSTX [19]. Various ideas of flow induction have also been discussed. An application of Thermo-Electric Magneto-Hydro-Dynamics (TEMHD) was proposed as the Lithium-Metal Infused Trenches (LiMIT) [20], and tested in HT-7 as the Flowing Liquid Lithium Limiter (FLLL) [21]. In the Actively Convected Liquid Metal Divertor (ACLMD), the Lorentz force is used to drive a flow [22]. However, the simplest flow induction methods might be those that take advantage of the force of gravity. Some examples of gravity-driven systems include a jet-drop curtain of liquid gallium, which was applied as the plasma limiter in T-3 M [23], a thin liquid film formed between two knife-edge guides [24], a guide-plate type liquid metal divertor, and a free fall type liquid metal shower divertor. The latter two were already proposed in 1986 [25].

Among these methods, we have chosen the free fall type liquid metal shower divertor. However, a simple shower seems not suitable for our purpose. Each jet in the shower narrows after acceleration by gravity. What is worse, a jet easily transforms to droplets due to the surface tension instability [26]. Use of wires, tapes, or chains as an Internal Flow Resistance (IFR) is effective to stabilize the jet. When a jet is falling along an IFR, the jet flow velocity finally reaches the terminal velocity, because the friction force balances the gravitational force. The basic idea of REVOLVER-D is to use the liquid metal shower jets stabilized by IFRs.

This paper describes the conceptual design of REVOLVER-D in FFHR-d1. The overall picture together with the details of the jets stabilized by IFRs and the limiter/divertor concept are described in the next section. Numerical evaluations of the permissible heat load, the liquid metal pump power, and the vacuum pressure are given in Section 3. The magnetic field environment surrounding the REVOLVER-D is discussed in Section 4. Finally, these discussions are summarized in Section 5.

2. The overall picture of REVOLVER-D

A bird’s eye view of the FFHR-d1 equipped with the REVOLVER-D is shown in Fig. 1. The REVOLVER-D is composed of ten similar units. One unit consists of a liquid metal pump, ducts, an upper unit (shower head with IFRs), a lower unit (pool), and a heat exchanger. Maintenance of the liquid metal pump, the upper unit, and the cooling panels in the heat exchanger is easy since these can be removed by simply pulling them up. It is also possible to use the large outer and/or upper ports, if the breeding blankets are already removed for maintenance. In the device center, a central vacuum vessel is installed and connected to the main vacuum vessel via ten inner ports equipped with maze neutron shields. This central vacuum vessel is designed to enhance the vacuum pump efficiency by minimizing the conductance between the main vacuum vessel and the vacuum pumps consisting of cryopanel units and Turbo Molecular Pumps (TMPs). The maze neutron shield protects the components in the central vacuum vessel from direct irradiation by 14 MeV neutrons, while maintaining a high conductance for efficient vacuum pumping. Although a detailed design work should be performed in future, it will basically have a maze structure as seen in Fig. 1. The cryopanel units, TMPs, liquid metal pumps, and High-Temperature Superconductor Central Solenoids (HTS-CS) are installed inside the central vacuum vessel. The main purpose of the HTS-CS is to shield the pumps from the strong magnetic field. A strong vertical magnetic field of 5 T exists in the central region of FFHR-d1 (with the present magnetic configuration), where liquid metal pumps and TMPs are installed. This magnetic field can be shielded by using the HTS-CS. The magnetic field distribution with or without HTS-CS will be discussed in Section 4. The cryostat for the HTS-CS is set inside the central vacuum vessel as shown in Fig. 1. There is a large space inside the cryostat for the HTS-CS and it is possible to install additional neutron shields to protect the SC coils from the streaming neutrons, if necessary. Detailed design studies on the HTS-CS, cryostat, supporting structure, and neutron shield, together with the neutronics simulation remain for future study.

In the heliotron configuration as in LHD and FFHR-d1, the so-called ergodic layer surrounds the Last-Closed-Flux-Surface (LCFS). A magnetic line of force started from just outside the LCFS travels inside the ergodic layer for more than several hundreds of meters even in LHD [4], which is four times smaller than the FFHR-d1. Therefore, if the liquid metal shower is set inside the ergodic layer as in Fig. 2, a significant portion of magnetic lines of force will finally hit a shower. Then, the plasma heading for the divertor region along the magnetic lines of force will also hit a shower and disappear. From this point of view, the liquid metal shower of REVOLVER-D plays a role of a limiter inserted into the ergodic layer. A similar idea has been already proposed as the Helical X-point Divertor (HXD)