REVOLVER-D: The Ergodic Limiter/Divertor Consisting of Molten Tin Shower Jets Stabilized by Chains

J. Miyazawa[1,2], T. Goto[1,2], T. Ohgo[1], T. Murase[1], N. Yanagi[1,2], H. Tamura[1], T. Tanaka[1,2], R. Sakamoto[1,2], S. Masuzaki[1,2], H. Tanaka[3], A. Sagara[1,2], and the FFHR Design Group

[1] National Institute for Fusion Science, 322-6 Oroshi-cho, Toki, Gifu 509-5292, Japan

[2] SOKENDAI (The Graduate University for Advanced Studies), 322-6 Oroshi-cho, Toki, Gifu 509-5292, Japan

[3] Nagoya University, Furo-cho, Chikusa-ku, Nagoya, Aichi 464-8603, Japan

E-mail contact of main author: miyazawa@LHD.nifs.ac.jp

Abstract. A new liquid metal divertor concept named the REVOLVER-D (Reactor-oriented Effectively VOLumetric VERtical Divertor) is proposed for the LHD-type helical fusion reactor FFHR-d1. The REVOLVER-D consists of the liquid metal shower of “sheath jets” decelerated and stabilized by an internal flow resistance of wire/tape/chain inside each of the jets. These are installed at 10 inner ports of FFHR-d1 to intersect the ergodic layer surrounding the last-closed-flux-surface. The plasma heading for the divertor region hits the shower and disappears. Then the full-helical divertor as in LHD becomes less necessary. Maintenance of the REVOLVER-D is easy since it is localized at the inner port and its main components are easily removed by simple up/down motion. Pure molten tin is the first candidate of the liquid metal for the REVOLVER-D, because of its low melting temperature, low vapor pressure, and high nuclear stability, *etc*. The permissible heat load of the REVOLVER-D is sufficiently high since it uses the flowing liquid metal as the plasma facing material. In this paper, the basic concept of the REVOLVER-D is described.

1. Introduction

The conceptual design activity on the helical fusion reactor, FFHR-d1, is ongoing [1-4]. The FFHR-d1 is basically similar to the Large Helical Device (LHD) [5] and designed based on the achievement of LHD in both areas of fusion technology and plasma physics. The major radius of the helical coils is 15.6 m and the magnetic field strength at the plasma center is ~6 T. The fusion output is supposed to be ~3 GW. The divertor is one of the fundamental devices in a magnetic fusion reactor. As for the divertor system of the FFHR-d1, there are at least two large issues. One is the high heat load and the other is the difficult maintenance of the three-dimensionally complicated structure of the helical divertor. Since the FFHR-d1 is 4 times enlarged from the LHD, in which the plasma-wetted area is ~2 m^2 [6], the plasma-wetted area in the FFHR-d1 is estimated to be $\sim 2 \times 4 \times 4 \sim 32$ m^2, as long as the divertor target plates are located at the similar position as in LHD. If we assume the radiation loss to be ~30 % as is often observed in high-density attached plasmas in LHD [7], then the averaged divertor heat load on the target plates due to the alpha heating power of 600 MW is calculated to be 600 MW × 0.7 / (32 m^2) ~ 13 MW/m^2. However, it is also observed in LHD that the divertor heat load is not uniform on the target plates, *i.e.*, it is asymmetric in both toroidal and poloidal directions [8]. The peak heat load becomes at least a few times larger than the averaged heat load and may exceed 20 MW/m^2. Even in the case of the latest water-cooled tungsten monoblock divertor with copper cooling pipes being developed for the ITER, the acceptable heat load is limited to 20 MW/m^2 [9]. If this tungsten monoblock divertor is to be applied to the FFHR-d1, it is inevitable to reduce the divertor heat load by enhancing the radiation loss and achieving divertor detachment [6,10]. However, since only a limited measurement and actuators will be available in the fusion reactor environment, it will be quite challenging to sustain the divertor detachment for more than 1 year, as is expected for a fusion reactor as the base power supply. Although we are struggling to realize the uniform divertor heat load profile by optimizing the magnetic field structure, this is still insufficient at this moment [11]. Furthermore, the helical divertor inherently has a three-dimensionally complicated structure and this makes its maintenance quite difficult. We need to find a feasible scenario to exchange the divertor target plates and cooling pipes, which are located at the inboard, outboard, lower, and upper sides of the torus, in a severe gamma-ray environment.

In parallel with the conventional divertor system described above, we are also considering a new divertor system using the liquid metal as the plasma facing material [12]. The acceptable heat load of the flowing liquid metal can be much higher than that of the solid materials [13,14]. To realize the easy maintenance, an "ergodic limiter" configuration has been chosen. In the conventional limiter configuration, the limiter is inserted so that the plasma confinement region, or the last-closed-flux-surface (LCFS), is determined. In the ergodic limiter configuration in FFHR-d1, the limiter is inserted to the thick ergodic layer surrounding the LCFS, which is already determined by the magnetic field produced by the external magnet coils. The inherently equipped thick ergodic layer is one of the important characteristics of the LHD-type magnetic confinement system. We can expect a strong impurity shielding effect of the ergodic layer [15]. This limiter is equipped with the vacuum pumping capability and therefore we call this the "ergodic limiter/divertor" configuration. Although the heat load on

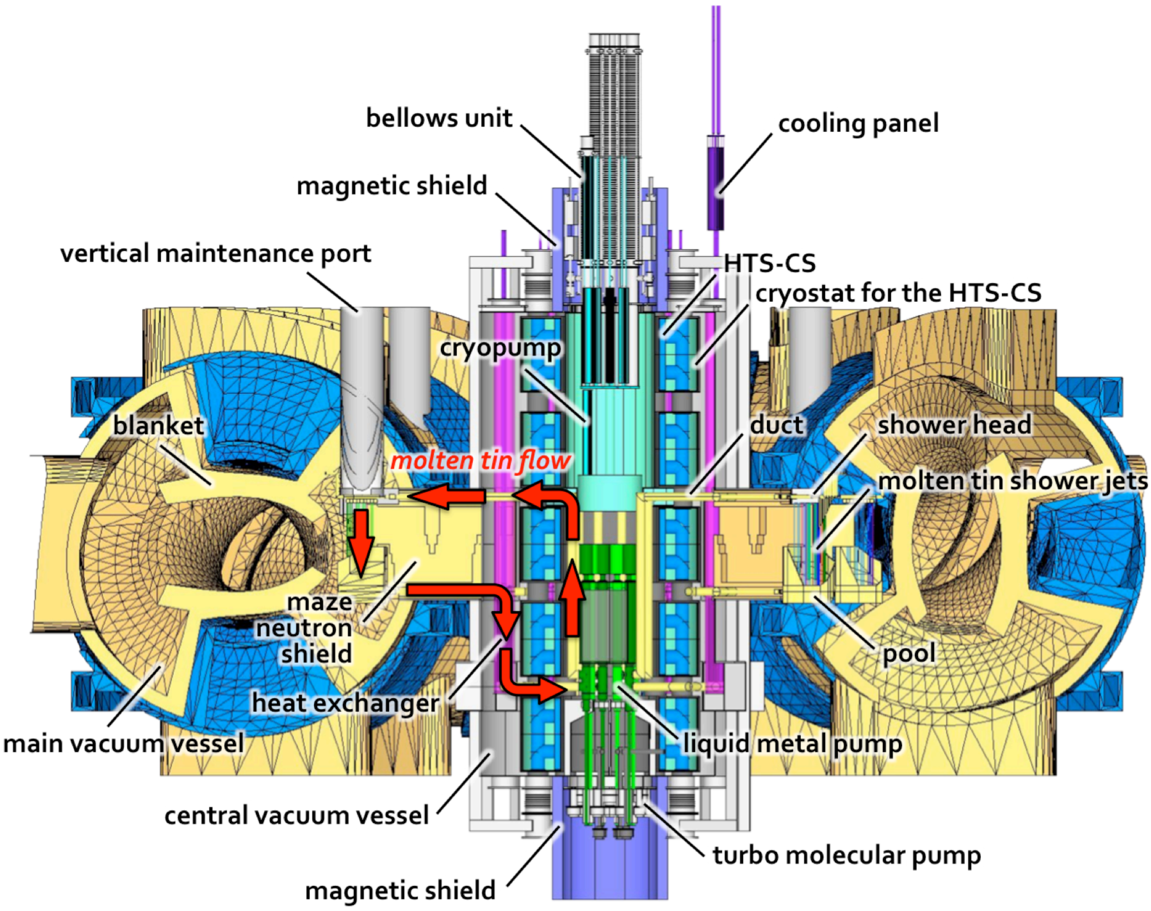

FIG.1. A schematic view of the FFHR-d1 equipped with the REVOLVER-D. The arrows denote the molten tin flow.

the ergodic limiter/divertor will be much higher than that on the helical divertor, the maintenance can be much easier since the devices are localized at 10 inner ports. This new liquid metal divertor concept is named the REVOLVER-D (Reactor-oriented Effectively VOLmetric VERtical Divertor). In FIG. 1, shown is a schematic view of the FFHR-d1 equipped with the REVOLVER-D. This paper describes the basic concepts of the REVOLVER-D.

2. Shower of Molten Tin Sheath Jets as the Plasma Facing Component

To simultaneously achieve a high heat load characteristic and a high vacuum pumping capability, we adopt a liquid metal shower [12] as the basic component of the REVOLVER-D. The free-fall type liquid metal shower divertor concept was already proposed 30 years ago by K. Maki [16]. In the REVOLVER-D, as will be shown in FIG. 4, the falling distance, h, of a jet is ~4 m. The gravity force accelerates the jets from the initial velocity of v_0 to $v = (v_0 + 2gh)^{0.5}$. In the case of v_0 = 4 m/s and h ~ 4 m, for example, the final velocity exceeds 9 m/s. This acceleration is not necessarily favorable from the points of view of narrowing jet diameter, unstable jet surface, and splashing at the pool receiving the shower. Furthermore, a normal free jet easily transforms to droplets due to the surface tension instability [17]. This is also unfavorable as the plasma-facing component. To decelerate the jet against the gravity and stabilize it, and to enhance the turbulence inside the jet at the same time, we insert an obstacle of wire/tape/chain into the jet as an internal flow resistance. The jet surrounding the obstacle forms a sheath-like structure. Therefore, we call this the “sheath jet”. We have recently started the basic study on the sheath jet by both simulation and experiment. Examples of the water sheath jet with wire/tape/chain inside are shown in FIG.2. A shower of sheath jets is used as the plasma-facing component in the REVOLVER-D. The shower can be a rigid wall for the plasmas slantingly entering the shower region along the magnetic lines of force (see FIG.3(a)). The majority of the heat load will be absorbed inside the shower and this is why we call this the “effectively volumetric divertor”. At the same time, the shower can be a transparent wall for the neutral particles generated on the surface of shower jets (FIG.3(b)). Therefore, it is possible to evacuate the neutral particles to behind the shower limiter. This is the basic concept of the limiter/divertor configuration that is capable of vacuum pumping. In the FFHR-d1, liquid metal showers are inserted to the inboard side of the ergodic layer at 10 toroidal sections, where the magnetic surfaces are horizontally elongated, as shown in FIG.4. The connection lengths of the magnetic field lines inside the ergodic layer in the FFHR-d1 are

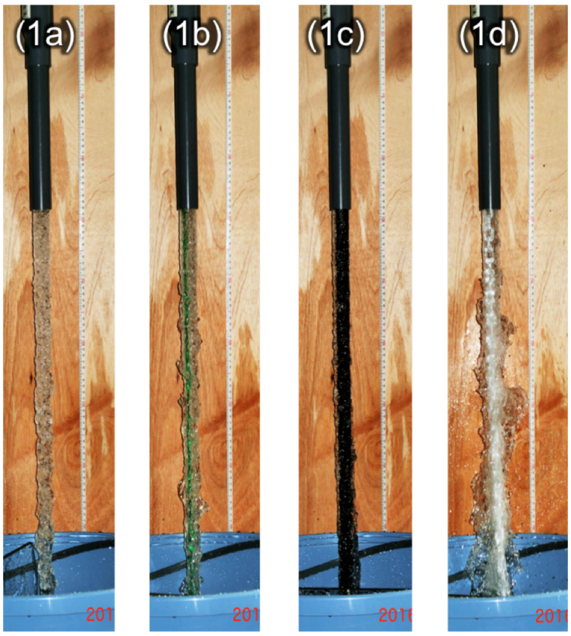

FIG.2. Vertical water jets of ~2,500 cc/s from a nozzle of 3 cm inner diameter (i.e., the flow velocity is ~3.5 m/s), (a) without inner obstacle (free jet), (b) with a nylon string, (c) with a thick rubber tape, and (d) with a plastic chain, inside each jet.

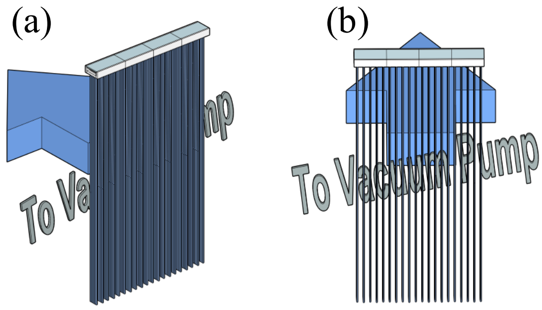

FIG.3. (a) The slanted view and (b) the front view of the shower jets.

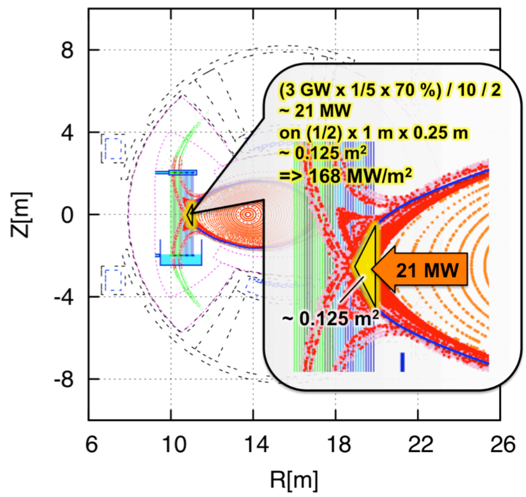

FIG.4. A schematic view of the shower unit inserted to the inboard side of the ergodic layer at the toroidal position where the magnetic surfaces are horizontally elongated.

4 times longer than those in the LHD [18] and exceed 100 m, even at the very edge of the ergodic layer [19], *i. e.*, the plasma moving along a magnetic field line in the ergodic layer travels more than one toroidal turn. At the same time, it also turns more than one time in the poloidal direction, since the rotational transform in the ergodic layer is > 1. Therefore, the majority of the plasma heading for the divertor region hits the shower and disappears. This means that the full-helical divertor as in LHD becomes less necessary. From FIG.4, we can give a minimum estimation of the plasma-wetted area to be ~0.125 m^2, *i.e.*, the triangle region that covers a part of the oval surrounding the ergodic layer region except the magnetic field lines of force escaping to the divertor region. Detailed estimation of the plasma-wetted area by the magnetic field line tracing is now underway. Nevertheless, we can give an upper estimation of the heat load on the liquid metal shower to be ~170 MW/m^2, where 70 % of the alpha heating power of 600 MW is assumed to be distributed to both sides of the 10 showers, *i.e.*, the plasma hits the shower from both toroidal directions of cw and ccw.

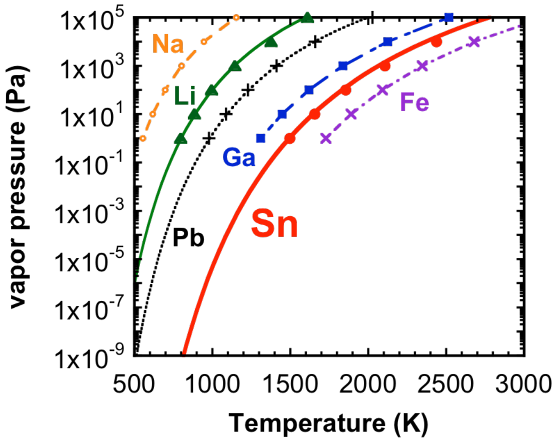

FIG.5. Vapor pressures of Na, Li, Pb, Ga, Sn, and Fe, as a function of the temperature. Curves of Li, Pb, and Sn are plotted according to the formulas given in [20], while the data shown by symbols are taken from the Wikipedia [21].

As the material of the liquid metal shower, tin (Sn) is considered to be the first candidate. The low melting temperature of ~505 K and the low vapor pressure are the main reasons of this selection. Among the metals with low melting points, *i.e.*, sodium (Na), lithium (Li), lead (Pb), and gallium (Ga), tin has the lowest vapor pressure, as is shown in FIG.5 [20,21]. Low material cost, low toxicity, no explosive reaction with water, and high nuclear stability are also the merits of tin. In FIG.6, shown is the contact dose rate after 30 days of 3 GW DT fusion operations in the FFHR-d1, calculated by the EASY-2005 [22]. The contact dose rate of tin, which is as high as ~1 kSv/h just after operation, decreases to ~ 1 mSv/h after ~30 years (~10^4 days).

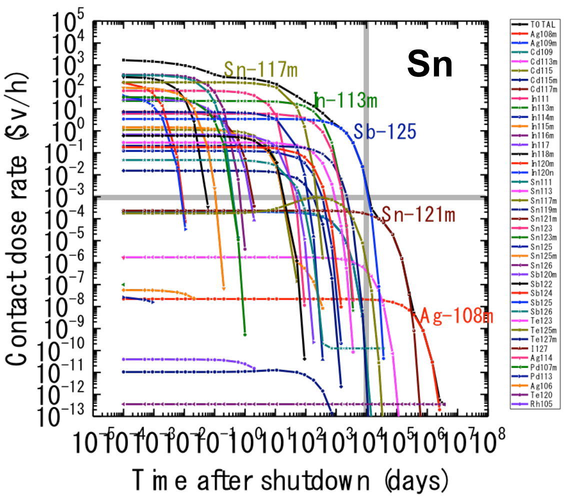

FIG.6. Contact dose rate of tin after 30 days of 3 GW DT fusion operations in the FFHR-d1, calculated by the EASY-2005 [22].

To evaluate the temperature of a molten tin jet receiving a high heat flux, we have carried out a numerical analysis using the finite element method simulation code ANSYS. The result is summarized in FIG.7. In this simulation, a cylindrical molten tin jet of 7 mm diameter without internal flow resistance was assumed. The initial temperature, T_0, was set to 573 K. The heat load, Q_{heat}, of 1 GW/m^2 with a cosine profile was applied at z = 10 – 20 mm from the top of the jet. The jet flow velocity, v, was varied from 1.4 m/s to 7.0 m/s. No gravity force was assumed and therefore the flow velocity was constant from the top (z = 0 mm) to bottom (z = 150 mm) of the jet. In the case of v = 4.2 m/s, for example, the maximum temperature, T_{max}, becomes ~2,000 K, and the downstream temperature, T_{DS}, at z = 150 mm becomes ~1,000 K. It should be noted that the temperature is not uniform at z = 150 mm. The averaged temperature, T_{ave}, is given by

$$T_{ave} = T_0 + \Delta T = T_0 + Q_{heat} / (Q_{mass}\ c_{Sn}), \quad (1)$$

where Q_{mass} and c_{Sn} are the mass flow rate and the specific heat of tin, respectively. As seen in FIG.7, T_{ave} is less than or equal to T_{DS}. The temperature increase, ΔT, as a function of the flow velocity is also depicted in FIG.7. Since ΔT is proportional to Q_{heat}, one can estimate ΔT at different Q_{heat}. In the case of Q_{heat} = 200 MW/m^2, which is similar to the case shown in FIG.4, for example, T_{max} and T_{ave} at v ~ 4 m/s are ~900 K and ~600 K, respectively. In this case, the vapor pressure is lower than 10^{-7} Pa (see FIG.5). To decrease T_{max} and T_{DS}, it is efficient to induce the turbulence in the jet and mix the hot and cold components. From this point of view, insertion of an internal flow resistance into the jet to form the sheath jet will be effective.

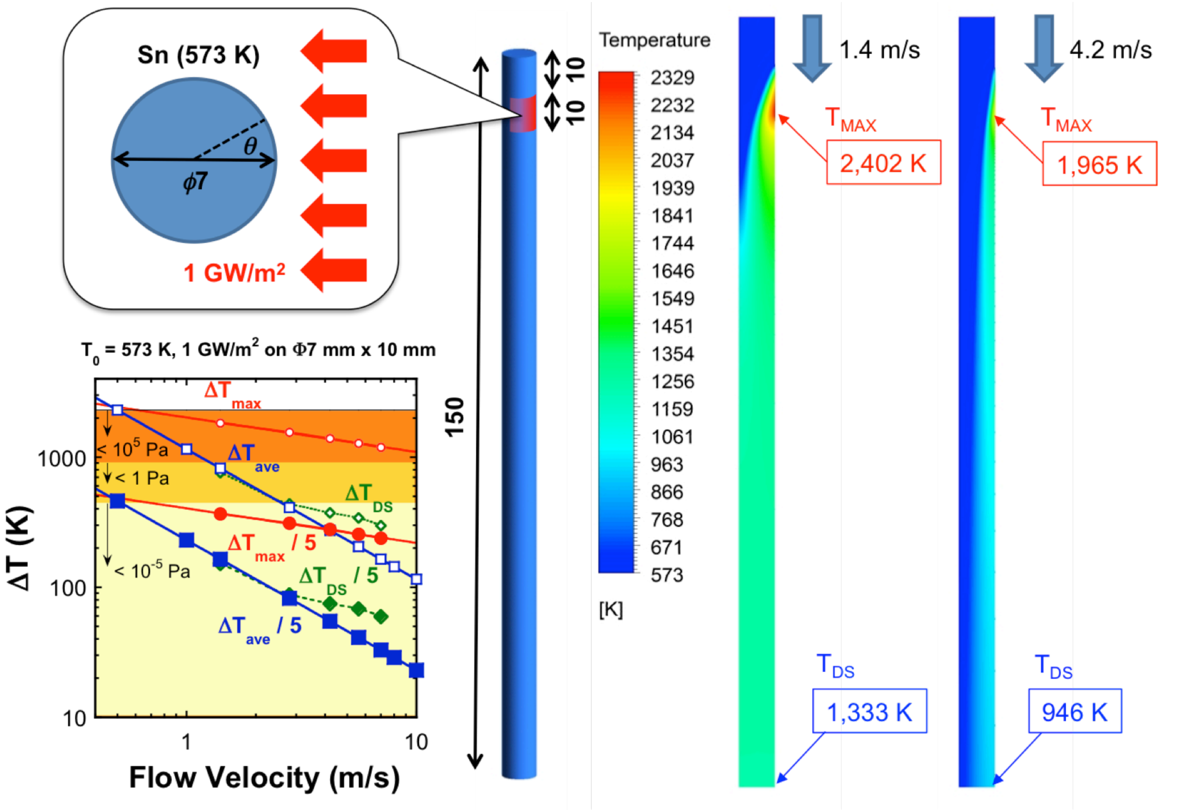

FIG.7. Summary of the results given by the finite element method simulation code ANSYS. The heat load of 1 GW/m^2 was applied at z = 10 – 20 mm of the molten tin flow of 7 mm diameter and 150 mm length. The initial temperature was fixed to 573 K while the flow velocity was varied from 1.4 m/s to 7.0 m/s.

3. The REVOLVER-D System

As shown in FIG.1, one unit of the REVOLVER-D is composed of (1) the liquid metal pump, (2) ducts, (3) the showerhead with arrays of internal flow resistance of wire/tape/chain to form the sheath jets, (4) the pool receiving the shower, and (5) the heat exchanger. To minimize the pump power, the liquid metal pump is installed in the central region of the FFHR-d1. Since the LHD-type heliotron device does not need central solenoids for current drive, which usually occupies the central region of the tokamak reactor, the central region of the FFHR-d1 is an open space. On the other hand, a strong magnetic field reaching ~5 T, which depends on the magnetic configuration, exists in the central region of the FFHR-d1. To operate the liquid metal pump at there, (6) the central solenoids made of high-temperature superconductor (HTS-CS) are also installed in the central space as the magnetic shield. The HTS-CS and its cryostat are installed inside (7) the central vacuum vessel. The central vacuum vessel is connected with the main vacuum vessel via (8) the maze neutron shields installed in 10 inner ports. To achieve a high vacuum pumping speed, it is necessary to minimize the conductance between the main vacuum vessel and the vacuum pumps. This is realized by installing (9) the cryopump unit and (10) the turbo molecular pump (TMP) unit inside the HTS-CS. Main features of these 10 components are summarized below.

(1) Liquid metal pump: The mass flow rate that should be driven by the liquid metal pump is determined by Eq. (1). In the case of the REVOLVER-D, we suppose T_0 = 523 K, ΔT = 200 K, Q_{heat} = 600 MW × 0.7 = 420 MW, and c_{Sn} = 260 J/(kg·K), respectively. Then, we obtain Q_{mass} ~ 8,000 kg/s ~ 29,000 ton/h. According to this estimation, 10 liquid metal pumps of ~3,000 ton/h at the maximum are necessary for the REVOLVER-D.

(2) Ducts: Tin shows a strong corrosivity when it touches with metals. On the other hand, the reactivity of tin with ceramics is quite low. Therefore, at least the inner surface of the ducts transferring tin should be covered with ceramics. Also from the point of view of the MHD drag force mitigation, one should use insulating pipes for the ducts. As seen in FIG.1, the ducts connect the central region and the plasma confinement region. Therefore, the tin flow inevitably suffers from a strong MHD drag force due to the transverse magnetic fields, if the ducts are made of conductive materials. Preliminary estimation of the pump power of the REVOLVER-D with insulating ducts resulted in the total pressure loss of ~1 MPa, in which the MHD loss is less than 0.2 MPa, and the total pump power of ~5 MW. In the case with the conducting ducts, the total pressure loss exceeds 70 MPa and the total pump power increases to ~370 MW. The latter case with the conducting ducts is apparently impermissible. Development of a double pipe, in which the outer metal pipe reinforces the inner ceramic pipe, is strongly desired.

(3) Showerhead: The arrangement of the shower of molten tin sheath jets is not fixed yet. It should be carefully arranged so that it works as the ergodic limiter/divertor. To obtain the optimized design of the shower, we are preparing both of the magnetic field line tracing code and the neutral particle simulation code.

(4) Pool: At one section of the REVOLVER-D, tin is falling with ~800 kg/s of the mass flow rate. The pool receiving the shower should be made of strong materials. At the same time, the inner side of the pool should be covered with ceramics, to prevent corrosion by tin. Suppression of the splashing of tin is remained as an important issue.

(5) Heat exchanger: Since the temperature increase of tin after plasma irradiation is supposed to be ~200 K, it will be possible to generate an electricity by using the proper heat exchanger and turbine system. We are considering a heat exchanger with removable

cooling panels as shown in FIG.1. The maintenance of the cooling panel can be performed by pulling them up/down.

(6) HTS-CS: To shield the strong magnetic field reaching ~5 T in the central region of the FFHR-d1, where the liquid metal pumps and the vacuum pumps are to be placed, the HTS-CS and its cryostat are installed in the central vacuum vessel. The HTS-CS can reduce the magnetic field strength to < 0.5 T. Then, it becomes possible to use ordinary magnetic shield materials to completely protect the liquid metal and vacuum pumps.

(7) Central vacuum vessel: Cryopump units, TMP units, and the cryostat of the HTS-CS are installed in the central vacuum vessel. This vacuum vessel is an additional component that does not exist in the LHD.

(8) Maze neutron shield: The main vacuum vessel and the central vacuum vessel are connected through 10 inner ports. It is necessary to keep high conductivity for vacuum pumping, and at the same time, to shield the HTS-CS from the direct irradiation by 14 MeV neutrons during plasma operation. To satisfy these requirements, maze-type neutron shields are being considered. Simulation studies on the neutron and neutral particle transport are needed for detailed design of the maze neutron shield.

(9) Cryopump unit: The vacuum pumping speed required for the cryopump unit as the main vacuum pump is supposed to be ~500 $Pa{\cdot}m^3/s$, in the FFHR-d1. To achieve this, the conductance between the main vacuum vessel to the cryopump unit should be as low as possible. Ten sets of the cryopanels of ~20 m^2 surface area are to be used in the FFHR-d1. Each of them operates for 1,000 s and absorbs 500,000 $Pa{\cdot}m^3$ of hydrogen isotopes. Then, the tritium inventory in a panel unit after the 1,000 s operations is 600 g. After that, it is pulled up and regenerated inside a tube while other 9 panels are working, *i.e.*, within 9,000 s.

(10) TMP unit: To evacuate the helium ash, which is generated at a rate of ~4 $Pa{\cdot}m^3/s$ during the 3 GW operation, 26 TMPs are installed at the bottom of the central vacuum vessel. The vacuum pumping speed of each TMPs is supposed to be 5 m^3/s.

4. Summary

The REVOLVER-D consisting of showers of molten tin sheath jets inserted to the inner ergodic layer at 10 toroidal sections, where the magnetic surfaces are horizontally elongated, has been proposed for the FFHR-d1. This will work as an ergodic limiter/divertor with high vacuum pumping capability under a high heat load condition. The basic concept and main features of the 10 important components of the REVOLVER-D are described. Details of the vacuum pumping design, the magnetic field profiles with or without the HTS-CS, and the pump power estimation of the liquid metal pumps, will be presented elsewhere. On the other hand, there are a lot of remained issues that should be solved, *e.g.*, basic studies on the sheath jet, magnetic field line tracing and neutral particle simulation for the optimized shower design, experiments using the sheath jet on the high heat load characteristic, on the MHD behavior in the strong magnetic field, on the plasma irradiation effects (sputtering, dust formation, hydrogen retention, vapor shielding, *etc.*), and on the comprehensive demonstration in a real plasma confinement device as the LHD. Studies on the transport of sputtered tin ions in the ergodic layer, splashing mitigation at the pool, and selection of suitable materials are also the important issues to be investigated. Nevertheless, the REVOLVER-D has a good possibility to realize the strong particle handling capability at a high heat load condition and the easy maintenance simultaneously.

References

[1] Sagara, Akio, et al., "Helical reactor design FFHR-d1 and c1 for steady-state DEMO", Fusion Eng. Des. **89** (2014) 2114.

[2] Sagara, Akio, et al., "Two conceptual designs of helical fusion reactor FFHR-d1A based on ITER technology and challenging ideas", 2016 IAEA Fusion Energy Conference (2016).

[3] Yanagi, Nagato, et al., "Helical coil design and development with 1000-kA HTS STARS conductor for FFHR-d1", 2016 IAEA Fusion Energy Conference (2016).

[4] Goto, Takuya, et al., "Development of a real-time simulation tool towards self-consistent scenario of plasma start-up and sustainment on helical fusion reactor FFHR-d1", 2016 IAEA Fusion Energy Conference (2016).

[5] Komori, Akio, et al., "Goal and achievements of Large Helical Device project", Fusion Sci. Tech. **58** (2010) 1.

[6] Miyazawa, Junichi, et al., "Role of recycling flux in gas fueling in the Large Helical Device", Nucl. Fusion **44** (2004) 154.

[7] Miyazawa, Junichi, et al., "Density limits for the core and edge plasmas related to the local temperatures in LHD", Fusion Sci. Tech. **58** (2010) 200.

[8] Shoji, Mamoru, et al., "Investigation of the helical divertor function and the future plan of a closed divertor for efficient particle control in the LHD plasma periphery", Fusion Sci. Tech. **58** (2010) 208.

[9] Schlosser, J., et al., "Technologies for ITER divertor vertical target plasma facing components", Nucl. Fusion **45** (2005) 512.

[10] Miyazawa, Junichi, et al., "Self-sustained detachment in the Large Helical Device", Nucl. Fusion **46** (2006) 532.

[11] Yanagi, Nagato, et al., "Divertor heat flux reduction by resonant magnetic perturbations in the LHD-type helical DEMO reactor", Proc. 24th IAEA Fusion Energy Conf. (San Diego, USA) (2012) FTP/P7-37.

[12] Miyazawa, Junichi, et al., "Liquid metal divertor concept consisting of vertical free-surface streams and a supersonic jet pump", Proc. 1st IAEA TM on Divertor Concepts (2015) P-7, and http://www-naweb.iaea.org/napc/physics/meetings/TM49934.html.

[13] Ida, Mizuho, et al., "Thermal-hydraulic characteristics of IFMIF liquid lithium target", Fusion Eng. Des. **63-64** (2002) 333.

[14] Shimada, Michiya, and Hirooka, Yoshi, "Actively convected liquid metal divertor", Nucl. Fusion **54** (2014) 122002.

[15] Morita, Shigeru, et al., "Effective screening of iron impurities in the ergodic layer of the Large Helical Device with a metalic first wall", Nucl. Fusion **53** (2013) 093017.

[16] Maki, K., "Liquid metal divertors", Tokamak concept innovations, IAEA-TECDOC-373, Vienna (1986) 87-92.

[17] Okino, Fumito, et al., "Vacuum sieve tray for tritium extraction from liquid Pb-17Li", Fusion Eng. Des. **87** (2012) 1014.

[18] Masuzaki, Suguru, et al., "The divertor plasma characteristics in the Large Helical Device", Nucl. Fusion **42** (2002) 750.

[19] Morisaki, Tomohiro, et al., "Numerical study of magnetic field configuration for FFHR from a viewpoint of divertor and edge field structure", Fusion Eng. Des. **81** (2006) 2749.

[20] Kondo, Masatoshi, and Nakajima, Yuu, "Boiling points of liquid breeders for fusion blankets", Fusion Eng. Des. **88** (2013) 2556.

[21] https://en.wikipedia.org/wiki/Sodium, https://en.wikipedia.org/wiki/Gallium, and https://en.wikipedia.org/wiki/Iron

[22] Forrest R.A., Gilbert, M.R., "FISPACT-2005: User manual", UKAEA FUS 514, and http://www.ccfe.ac.uk/assets/Documents/UKAEA-FUS-514FINAL.pdf