DEVELOPMENT PLAN AND CURRENT STATUS TOWARD THE REALIZATION OF STEADY-STATE FUSION REACTOR BY HELICAL FUSION

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1. DEVELOPMENT PLAN

Helical Fusion Co., Ltd. (HF) is a Japanese private fusion startup established in 2021. The goal of HF is to implement steady-state fusion reactors in society. To achieve this, HF is developing a steady-state helical fusion reactor based on the public knowledge of the design studies of the FFHR series [1] and the experimental data accumulated in LHD (Large Helical Device) [2]. HF plans to start operation of FPP (Fusion Pilot Plant) in 2034, leading to the realization of FOAK (First-Of-A-Kind) steady-state fusion reactor and its increased production by the middle of the 21st century.

The FPP is similar to the design described in our previous paper [3]. The device parameters, such as device size and magnetic field strength, are being modified. High-Temperature Superconducting (HTS) magnets and liquid metal blankets are employed in the FPP. Plasma heating is only Electron Cyclotron Heating (ECH) with gyrotrons. Neutral Beam Injection (NBI) and Ion Cyclotron Heating (ICH) are not assumed. Solid hydrogen pellet injection is used for fueling, together with the Direct Internal Recycling (DIR) system, in which exhaust gas is purified, pressurized, and utilized for fueling again without isotope separation. The liquid metal used as the blanket coolant and tritium breeder is an alloy of tin, lithium, and a small amount of lead as a neutron multiplier [4]. Tin was selected as the base material because of its low melting point, vapor pressure, toxicity, and hydrogen isotope solubility. A portion of this liquid metal coats the blanket first-wall, including the divertor region with a free surface flow. This will inhibit damage to the blanket first-wall and, at the same time, stabilize the recycling of hydrogen isotopes. Diverter plasma is also received by the liquid metal free surface flow of the blanket first-wall, so it can withstand a large heat load without installing special divertor equipment. In addition, because our liquid metal alloys have low hydrogen isotope solubility, the tritium gas produced in the liquid metal alloy is immediately released into the vacuum vessel and incorporated into the fuel recirculation by the DIR system. We call it the DIVER (Direct InVEssel Recycling) system. Compared to the regular DIR system, our DIVER system does not need to include a tritium extraction and separation system.

Before starting the construction of FPP, we need to establish individual technologies on the HTS magnet, liquid metal blanket, gyrotron, hydrogen ice pellet injection, and DIVER. Individual Research and Development (R&D) stages are underway for these technologies. As the next step before FPP, a small device called FED (Final Experimental Device) will be developed to integrate and demonstrate these new technologies. The main objectives of the FED are to demonstrate the feasibility of HTS conductors for helical coils and the steady-state operation of high-temperature plasmas surrounded by flowing liquid metal for long periods up to several days. The plasma performance and/or demonstration of a high Q is not in the scope of FED. The device size of FED is minimized to reduce the development cost while keeping enough size to demonstrate the 100 kA class HTS conductor being developed for FPP and to demonstrate the coexistence of the liquid metal first-wall and high-temperature plasmas. The FED will be built in the next few years and will be operational during the 2020s to demonstrate its goals.

2. CURRENT STATUS

HF is conducting four main R&D projects: (1) Magnet, (2) Blanket, (3) Plasma heating, (4) Fueling and vacuum evacuation. The current status of R&D activities on (1) to (4) are described below.

(1) Magnet: The development of HTS UROCOIC (Unitized Reinforcing Outer Cover On Internal Components) conductors is underway within the framework of the SBIR program from 2023 to 2027, promoted by the Japanese Ministry of Education, Culture, Sports, Science and Technology, with a budget of 2 billion JPY. A typical UROCOIC conductor consists of ~170 of 12 mm width REBCO tapes together with two cooling channels and SUS (or BeCu) tapes for reinforcement, with a cross-section of 31×37 mm^2. A hairpin-shaped straight conductor (Fig. 1) has been fabricated using the WISE (Wound and Impregnated Stacked Elastic tapes) conductor that is the

former version of the UROCOIC conductor consisting of 60 REBCO tapes of 12 mm width. This straight conductor was successfully energized to 40 kA at 8 T - 6 K in the large conductor testing equipment in NIFS (Fig. 2) [5]. A Double Pancake (DP) coil is currently being fabricated using an "uninsulated" UROCOIC conductor. Energization testing of the DP coil is scheduled for June 2025. After that, the fabrication of a helical coil with a major radius of ~1.1 m that is applicable to the FED will begin. The design of a helical coil winding machine for this is underway. The helical coil will also be fabricated using uninsulated UROCOIC conductors. Since the time variation of the current distribution in uninsulated HTS coils is a complicated problem, numerical simulation on this is also being prepared.

Figure 1: The hairpin-shaped straight conductor.

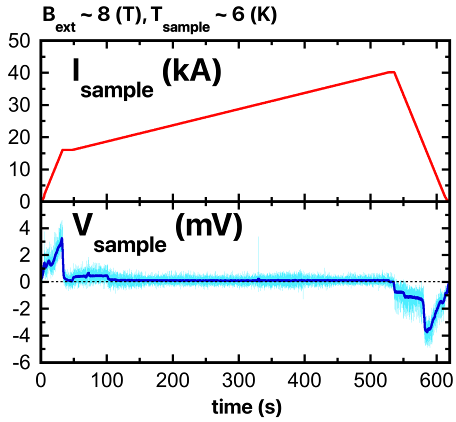

Figure 2: Waveforms of (a) current and (b) voltage in a straight conductor energization test.

(2) Blanket: HF is developing the blanket for neutron transport simulations and liquid metal experiments. We have established a method to incorporate complex 3D CAD data of helical fusion reactors into a neutron transport simulation code [6]. Subsequently, we have been working on evaluating neutron shielding, TBR (Tritium Breeding Ratio), residual radioactivity, and so on, making full use of the fast computing power of Amazon Web Service (AWS). For liquid metal experiments, we are developing high manganese steel as a non-magnetic low activation steel material [7], porous materials to control the liquid metal flow in the breeding blanket, an original crane system for maintenance, and a new liquid metal pump system using pressurized gas that has been named GALOP (GAs-driven Liquid metal OPeration). R&Ds on steady-state liquid metal circulation by the GALOP system, material corrosion tests in the flow field, and wettability of the blanket first-wall will be conducted in the experimental apparatus shown in Fig. 3, which will be operational this spring.

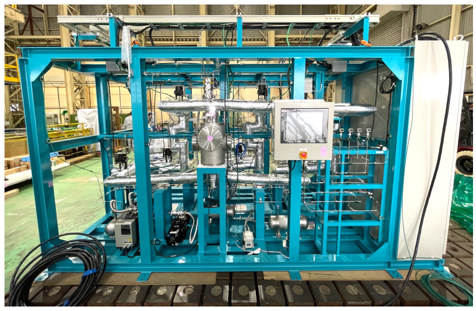

Figure 3: An experimental apparatus equipped with the GALOP system.

(3) Plasma heating: HF is currently developing a high-frequency gyrotron of ~200 GHz, which will be applicable for plasmas confined in high magnetic fields of 7 – 8 T. The gyrotron system will be fully simulated using electromagnetic field analysis software, and it will be simplified as much as possible to suit mass production and low manufacturing costs.

(4) Fueling and vacuum evacuation: HF is currently working with NIFS on the design and development of a multi-barrel solid hydrogen pellet injector and DIVER system.

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