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Design of a water-cooled tube for high-power and long-pulse radio frequency ion source

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ABSTRACT

The radio frequency (RF) driven ion source is a promising solution to the neutral beam injectors of ITER and future fusion reactor. Because the demanded RF power is so high (> 50 kW for one driver), a copper-made Faraday screen is installed inside the low dielectric tube to protect it against the plasma heat load. However, the Faraday screen may decrease the RF power transfer efficiency due to electromagnetic shielding and induced eddy current. Especially during the long-pulse experiments of plasma generation, the high heat load on the Faraday screen limits the increase of RF input power. Hence, a design of the water-cooled tube is proposed to avoid using the Faraday screen. The water-cooled tube should be able to suffer the plasma heat load by itself. Hence, the cooling circuit of the tube is designed and estimated through a fluid-thermal analysis. The water inlets with tangential injection direction are located inside the metal flanges. Such a design can induce a swirling flow around the tube, which can cause a more uniform temperature distribution and a lower peak temperature on the tube. In order to control the stress along the joints between the metal and the ceramic, the Kovar alloy (an iron-nickel constant expansion alloy) is chosen for the metal flanges, which has a similar thermal expansion coefficient with the ceramic. The thermo-structural analysis indicates a tolerable thermal stress on the ceramic layers of the designed tube under a uniform heat load of 30 kW.

1. Introduction

Neutral beam injection (NBI) is a main auxiliary heating method for the magnetic confinement fusion devices. The research aim of NBI system is the constant pursuit of high-power and long-pulse operation. For example, the heating neutral beam injectors (HNBs) of ITER are designed to deliver a D^0 beam of 16.7 MW at 1 MeV for up to 3600 s [1,2]. At such a high energy, accelerated negative ions must be used to achieve an acceptable neutralization efficiency. Only the type of negative ion source with Cs seeding can meet the required extracted D^- current densities of 285 A/m^2. For sufficient production of negative ions, another key factor is the powerful and stable plasma driver. A type of radio frequency (RF) driven ion source, that has been developed at IPP, Garching, Germany for twenty years [3–5], is chosen for ITER. Compared to the traditional arc driven ion source, the main advantage of RF driven ion source is that no filaments are used during operation. Hence, it can avoid the periodic maintenance of the filaments and the tungsten contamination on the Cs layer [6].

For the IPP type of RF driven ion source, multi RF drivers are directly attached to an expansion chamber to form the demanded plasma density. As shown in Fig. 1, each driver is a cylindrical tube and consisting of ceramic (Al_2O_3) lateral wall and a metal back-cover [7]. An RF coil is wound around the outside of the ceramic tube. The RF fields generated inside the driver together with the primary electrons ionize the working gas and create an inductively driven plasma. The RF power density for such type of RF driver is high to 10–15 W/cm^3. Hence, an actively cooled Faraday screen (FS), made of copper, is placed inside the driver to protect the ceramic tube from the plasma heat load. In addition, the FS back plate has to bear the impinging of back-streaming positive ions. But the metal FS will shield RF wave into the driver and induce eddy current loss. To improve the RF power transfer efficiency, the FS is slotted orthogonally with respect to the RF coil, and the thickness of FS should be as thin as possible. The items of thin wall, multi cooling channels, and special shape of the slots bring a large challenge to the machining of FS. Thus, the FS is the most critical component of the RF source during the high-power and long-pulse operation.

Since the FS reduces the RF power transfer efficiency inevitably and demands a great cooling capability on the thin wall. The FS introduce another problem of copper sputtering which also induces the

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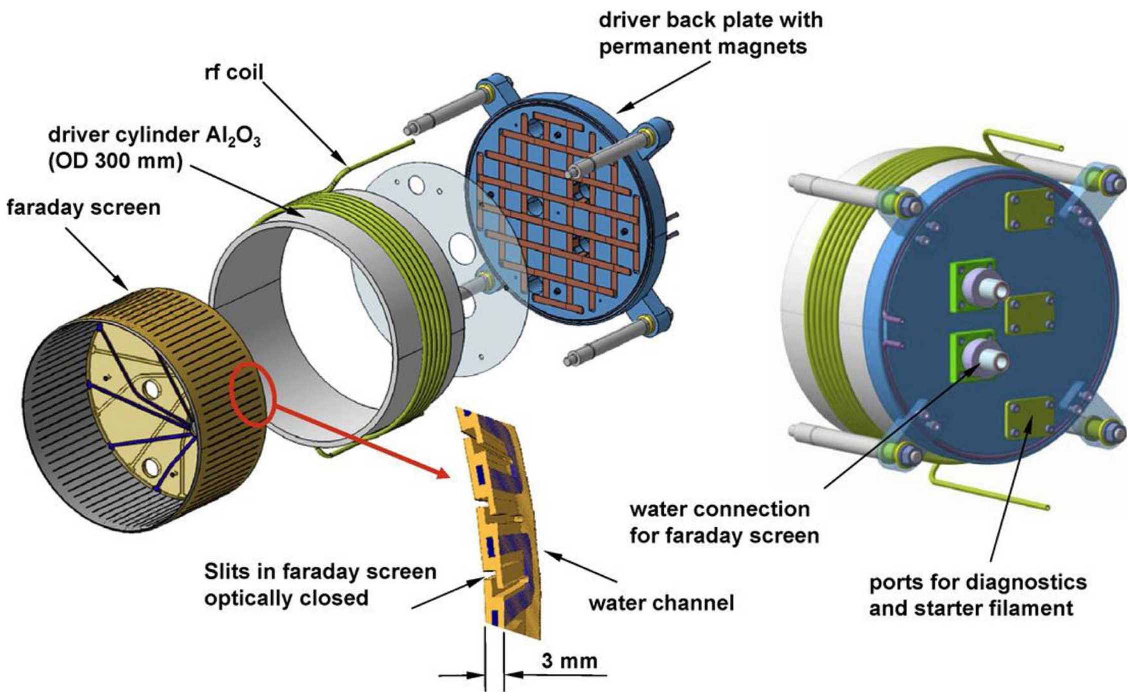

Fig. 1. The exploded view of the RF driver used in the IPP type of negative ion source [7], right side complete assembly, left side exploded view from inside.

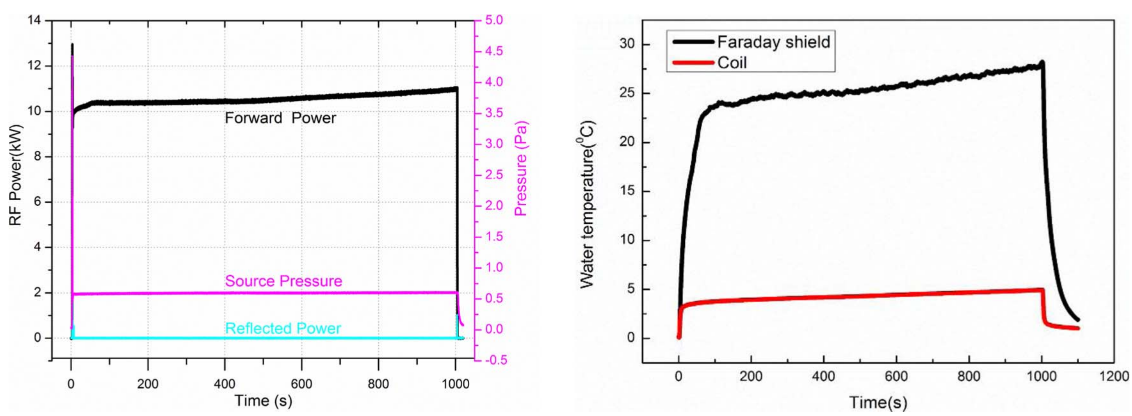

Fig. 2. The waveform of the long-pulse plasma discharge in the RF ion source on HUNTER (left) and the temperature raise of the cooling water during this shot (right).

contamination on the Cs layer, so additional treatment of molybdenum coating on the FS surface is required [8]. Here a new type of RF driver is designed to avoid the presence of FS. To solve the problem of the plasma heat load, the ceramic tube is designed to have an internal water-cooled structure. Because of the high hardness and brittleness as well as non-conductivity, the ceramic material is difficult to machine in conventional methods. Hence, several simple designs of the water-cooled structure are first considered and analyzed with the fluid-thermal models. The manufacturing scheme of the selected design was discussed. Finally, the feasibility of the design was estimated according to the simulation results of thermal stresses.

2. Traditional RF plasma driver test and analysis

Considered the advantages of RF driven ion source and the necessity of negative ion source, a small test bed “HUNTER” (Hefei Utility Negative ions Test Equipment with RF source) has been set up at Institute of Plasma Physics, Chinese Academy of Sciences (ASIPP) [9]. In the initial stage, the HUNTER negative ion source conservatively adopts a similar structure of the IPP type. However, except for gaining the operation experience, HUNTER is devoted to some crucial issues of the RF driven negative ion source, such as the improvement of RF power transfer efficiency, the enhancement of the extracted negative ion current density, and the promotion of the beam properties (e.g., electron to negative ion ratio, beam uniformity). So far, the assembly and the integrated commissioning of HUNTER have been finished.

As soon as the RF ion source was available, the plasma generation experiments were carried out extensively without the extraction system [10,11]. The input power from a 1 MHz RF power supply was inductively coupled to the driver through a matching network. During these experiments, various operation parameters were optimized to produce a stable plasma with an extremely low reflected power. Different diagnostics like Langmuir probes, optical emission spectrometer, water flow calorimetry were equipped to measure the plasma parameters. Finally, a hydrogen plasma of density $3.5 \times 10^{17}\,m^{-3}$ was measured in the expansion region by launching 50 kW power into the driver. Through the water flow calorimetry, the heat load on the FS was measured to be around 50% of the RF input power and the ratio was similar to the measurements on other test beds [12–14].

Such a high-power deposition on FS limited the RF input power during the long-pulse experiments. Taking a shot of 1000 s plasma generation as an example (shown in Fig. 2), the RF input power was