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Recent Long-Pulse Test Results of KSTAR ICRF Antenna with Active Cooling

Y.D. BAE, J.G. KWAK, J.S. YOON, and S.J. WANG
Nuclear Fusion Research Lab., Korea Atomic Energy Research Institute,
150 Deokjin-dong Yuseong-gu Daejeon, KOREA, 305-353, ydbae@kaeri.re.kr

1. Introduction

KSTAR ICRF (Ion Cyclotron Range of Frequency) system is being developed for the high-power and long-pulse operation. For a 300 s operation at a high power of 6 MW, the antenna has many cooling channels inside the current strap, Faraday shield, cavity wall, and vacuum transmission line (VTL) to remove the dissipated RF loss power and incoming plasma heat loads. In the previous test campaign, the standoff capability was increased to 31.2 kVp, 300 s from 24.3 kVp, 300 s by applying water cooling on the ICRF antenna, but it was limited by an overheating of the vacuum feedthrough (VF) and the transmission line of the unmatched section which did not have cooling channels. During the recent RF test campaign (campaign-8), the cooling system for the VF and the transmission line of the unmatched section was developed to enhance the cooling capability. The cooling channels for inner conductors of VF and the transmission line were carefully designed and installed inside their inner conductors, which were connected in series. Outer conductors near the current maximum were also water-cooled by using Al cooling blocks which have a cooling channel inside them. The high power and long pulse capabilities of the antenna were experimentally estimated with active cooling on both of the antenna and the unmatched transmission line.

2. Water-Cooling of the Antenna and Test Section

The antenna has many cooling channels inside Faraday shield, current strap, cavity wall, and VTL to remove the dissipated RF loss power and incoming plasma heat loads. The Faraday shield consists of a single layer of water-cooled tubes covering a pair of toroidally adjacent straps. The tube diameter is 15.9 mm with a wall thichness of 1.25 mm, and it is copper-plated to reduce electrical losses. Each of the two shield sections consists of 33 tubes. The 3 Faraday shield tubes in each section are cooled in parallel and the two sections are cooled in series, which are connected to all cooling channels embedded in front edges of two septa and upper plate and lower plate of the cavity box. The left and right walls and center wall of the cavity box provide the cooling water path to the Faraday shield tube. The surface of the cavity is plated with copper to reduce the RF losses. The current strap has cooling channels along both edges, and channels are connected in series through those of the center conductors of upper and lower VTLs. The VTL has water cooling channel inside the center conductor featuring a coaxial tube. The cooling water for 4 current straps is distributed in parallel through a manifold embedded in the back plate of the cavity.

During the recent RF test campaign (campaign-8), the high voltage test with a long pulse duration of 300 s was performed using the test circuit as shown in Figure 1. The inner conductors of the VF and bottom test line were water-cooled as shown in Figure 2. Cooling water was supplied from the end of the stub tuber and U-turned at the end of VF inner conductor. Outer conductors of bottom/top VFs and bottom transmission line on which a standing wave was gernerated were also water-cooled by attaching Al block which has a concave surface and a cooling channel, as shown in Figure 3.

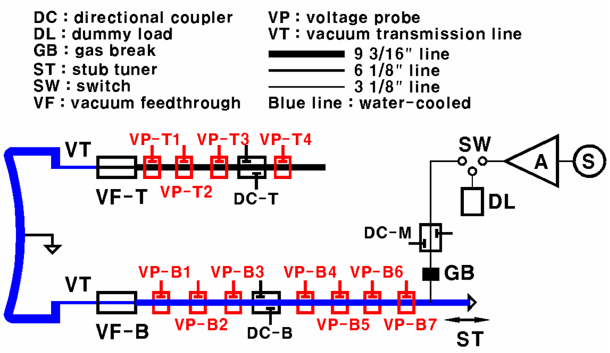

Figure 1. Schematic of the RF test circuit for the campaign-8.

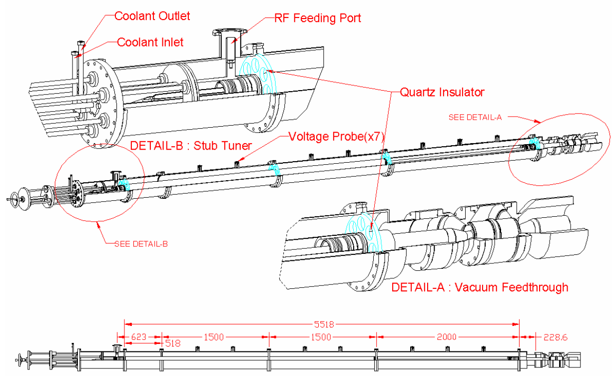

Figure 2. Cut-away view of bottom line. Cooling channels are shown inside the inner conductors of VF and transmission line.

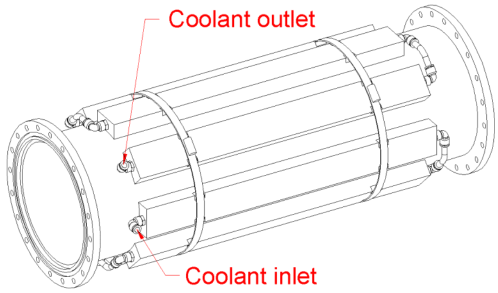

Figure 3. Water cooling of the outer conductor of a transmission line by using several Al cooling blocks connected in series.

3. RF Test with a Water-Cooling

The 15 RF tests of the antenna were performed during the test campaign-8 at a frequency of 30 MHz. As shown in Figure 1, a bottom half of the current strap-1 was connected to the RF source and other three straps were shorted at the input ports. The unmatched line section from stub tuner to vacuum feedthrough was pressurized with N_2 gas up to 3 kgf/cm^2 to increase standoff voltage. During the RF pulse, cooling water was fed on the antenna, the VF and the transmission line, and temperatures at several positions of the cavity outer wall and transmission line were measured by thermo-couples. The line voltage, forward and reflected powers, and RFTC pressure were also measured. For the conditioning of the antenna and the VTL, about twenty RF pulses were applied at low power range just before applying the main RF pulse. After the conditioning, the main test pulse was applied to the antenna, and its power was gradually increased shot by shot. As a test result of the maximum standoff voltage for a 300-s duration, the time evolutions of the forward and reflected powers, the maximum peak voltage, the maximum temperature of the antenna, and the vacuum pressure of the test camber are shown in Figure 4.

During the pulse testing, the reflected power was continuously increased as shown in Figure 4(a). It was caused by a temperature increase on the VVCs (vacuum variable capacitors) of input matching circuit of the main amplifier of the RF source. So an active tuning of VVCs was needed to reduce the reflected power. The maximum standoff voltage was 41.3 kVp for 300-s operation (Figure 4(b)), which is much higher than that of the previous campaign of 31.2 kVp. The maximum standoff voltage for 20-s pulse was 46.0 kVp. The voltage of 41.3 kVp is equivalent to a heating power of 7.4 MW in the case of a plasma loading of 6 Ω/m. The temperature of the cavity wall increased to 61 °C from an initial temperature of 26 °C, and it was not saturated but slightly increasing (Figure 4(c)). The vacuum pressure was saturated at below 6.9×10^{-6} mbar (Figure 4(d)). The limitation of a higher voltage testing was mainly caused by the maximum available output power of the RF source and breakdown on the ceramics of the vacuum feedthrough.

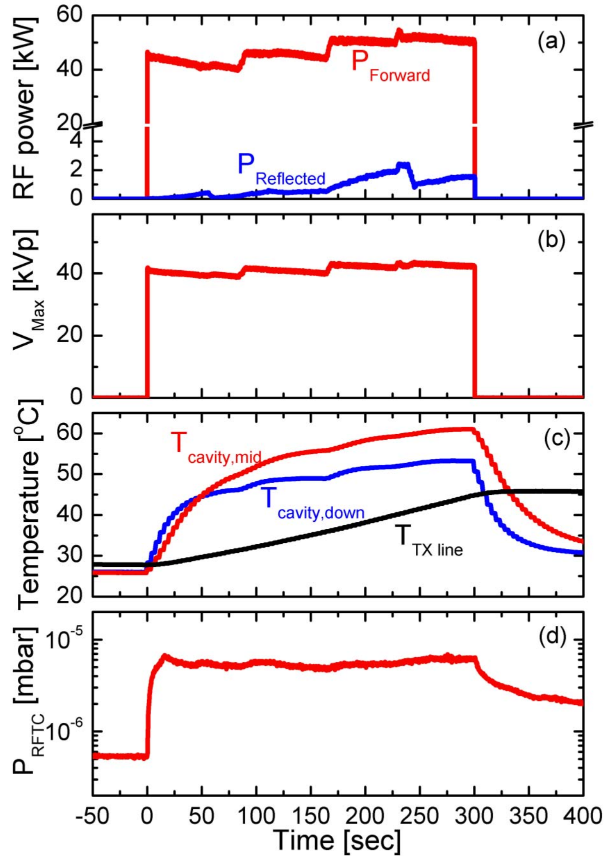

Figure 4. Time evolutions of the RF powers (a), line voltage (b), temperatures of the antenna cavity (c), and vacuum pressure of the RFTC (d) measured during 300-s long-pulse duration.

4. Conclusion

The test results show the standoff voltage of 41.3 kVp for a pulse length of 300 s, and 46.0 kVp for 20 s, which exceed the design requirement. Nevertheless, we should increase a standoff voltage to a higher level, because the standoff voltage achieved in vacuum should be much degraded in plasma environment. As future works, similar RF test will be performed at a higher RF voltage by using another RF source which has higher capability of power, and two-strap feeding experiment will be also performed.