COMPLETION OF DC 1 MV POWER SUPPLY SYSTEM FOR ITER NEUTRAL BEAM TEST FACILITY

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Abstract

In order to realize the DC 1 MV power supply system for ITER neutral beam injector (NBI) and NB test facility (NBTF), insulation technologies in oil, gas, vacuum and with water have been developed. To supply cooling water and high-temperature water, mechanical and electrical properties of fiber reinforce plastic (FRP) with water absorption was clarified. The mock-up of FRP tube was fabricated and pressure tightness and voltage capability was confirmed. As for high-temperature water supply to the plasma grid, the water resistivity up to 180 ^{o}C was experimentally measured and the high-temperature water channel was successfully designed. Based on those developments, manufacturing and installation for the power supply components for the NBTF/MITICA has been progressed and completed. Finally, to verify the voltage holding capability of the DC 1 MV power supply component, high-voltage test has been started by filling SF6 gas inside the components. That was the first high-voltage test in the NBTF/MITICA power supply under the assembled configuration with all components procured by Japan. As an initial test, high-voltage of DC 1.2 MV was applied on the DC generators and DC filter. As a result, stable voltage holding without breakdown for 1 hour was successfully confirmed.

1. INTRODUCTION

The neutral beam injector (NBI) is an essential system for plasma heating and current drive in fusion devices such as ITER. In the ITER NBI, the high power deuterium negative ion (D^-) beams with 1 MeV, 40 A (200 A/m^2) for 3600 sec [1] is required. This requirement is much higher than those achieved in the existing devices. For instance, the beam energy is twice and the pulse duration is 100 times compared with JT-60U [2-4]. Target parameters were closely obtained individually in several experimental devices [5-7]; however, all parameters have not been achieved simultaneously yet. Since there is such a large gap between the present achievement of existing NBI and the ITER requirement, the NB test facility (NBTF) is now being constructed in Consorzio RFX in Padova, Italy in order to verify the required performance in the ITER NBI.

Japan is in charge of procurement of high-voltage components of DC 1 MV power supply system both for the NBTF/MITICA (Megavolt ITER injector concept advancement) and the ITER NBI. In this power supply system, several insulation technologies have been developed to attain DC 1 MV insulation, namely, oil insulation in transformers in DC generator [8-10], gas insulation in transmission line (TL) [11] and vacuum insulation in high voltage (HV) bushing [9, 11]. As the results of those R&Ds, generation and transmission of DC 1 MV from the DC generator to the beam source through the TL and HV bushing were established, however, there was a remaining issue; an insulation design of cooling water supplied from the grounded potential to higher potential at 0.2 MV ~ 1 MV of the beam source. Originally, an alumina tube with 500 mm in a length was developed for electrical insulation for the water service line. However, handling of a number of alumina tubes (>140 tubes) during assembly and shipping of the water service line. Thus, fiber reinforced plastic (FRP) tube was considered to be the alternative with better handling. In case of the FRP, water absorption was a concern to apply as the insulating tube. In order to confirm the availability of FRP as the insulating tube, mechanical and electrical properties with water absorption was an issue for the detailed design. In addition, high-temperature water (180 ^{o}C) must be supplied to the beam source in parallel with cooling water, since the plasma grid (PG) is required to have a constant temperature up to 150 ^{o}C during long-pulse duration of 3600 s in order to sustain surface production of negative ions on the PG. Generally, as a temperature of high-purity water increases, the resistivity decreases, which causes higher leak current resulting in boiling of the high-temperature water even with high pressure. To establish the design for the high-temperature water line, measurement of the resistivity of the high-temperature water up to 180 ^{o}C was one of technical issues.

In this paper, recent progress on development, manufacturing and test of the DC 1 MV power supply the last two years. Overview of the DC 1 MV power supply system for the ITER NB is described in Section 2. Development of insulating tube for cooling water and the design of the high-temperature water supply are described in Section 3. Finally, the installation and the latest result of the high-voltage test of the assembled power supply component are reported in Section 4.

2. DC 1 MV POWER SUPPLY SYSTEM FOR ITER NBI

Figure 1 shows overview of the 1 MV power supply system and the beam source in the NBTF/MITICA which is identical to the ITER NBI. A high voltage of DC 0.2 MV is produced in a DC generator (DCG). The DCG in outdoor consists of an oil-immersed step-up transformer and a gas-insulated rectifier with diode stacks. By connecting five DCGs in series, DC 1 MV is generated. Five output conductors from each DCGs, having potential of 0.2 MV, 0.4 MV, 0.6 MV, 0.8 MV and 1 MV, respectively, are connected to the DC filter in which

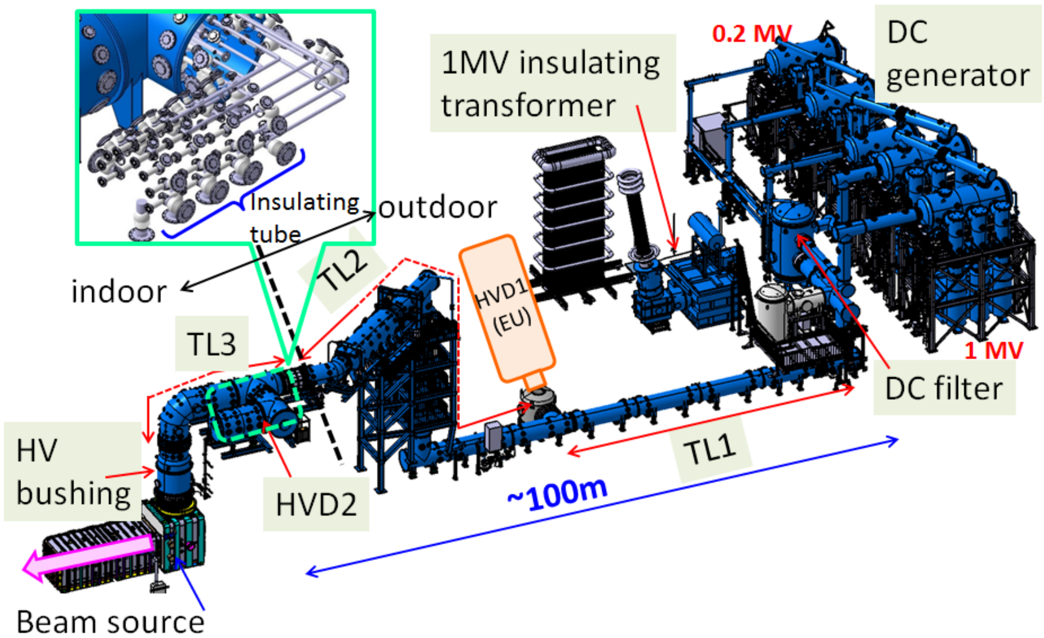

Figure 1 Overview of the DC 1 MV power supply system for the ITER NB.

overvoltage and ripple are suppressed to be less than 10 %p-p of DC output voltage.

As shown in Fig.1, in the upstream area of TL (TL1), five high-voltage conductors from DCGs of 0.2 MV to 1 MV are allocated inside the pressurized tank filled with SF_6 gas at 0.6 MPa (abs.). In the final part of the TL1, conductors from power supplies for negative ion production, which are mounted on the high-voltage deck 1 (HVD1) procured by EU, are joined with the high-voltage conductors from DCGs. Here, AC power for negative ion production must be provided from the ground potential to the power supplies on the HVD1 at 1 MV through the 1 MV insulating transformer. The second part of TL (TL2) having horizontal and vertical part penetrates the building wall. Inside the building, cooling water and hydrogen/deuterium gas are provided from the grounded potential to 1 MV through high-voltage deck 2 (HVD2), where more than 140 insulating tubes are connected in water and gas lines at five different potentials (0.2MV ~1 MV). Pipes for water and gas are joined with the conductors from DCGs and HVD1 in the final part of TL (TL3). Thus, all conductors and pipes concentrates in TL3 taking into account the insulating distance between each conductors and are introduced to the beam source in vacuum through the HV bushing consisting of five-stage insulator column and internal conductors is installed at the end of the TL acting as the insulating feedthrough between gas-insulated area and vacuum.

3. DC 1 MV INSULATION IN WATER SERVICE LINE

3.1.COOLING WATER SUPPLY WITH INSULATING TUBE

During long-pulse operation, heat removal in the beam source at each potential is required. For instance, cooling water with a mass flow of 33 L/s is required for the components at 1 MV potential such as the negative ion source, RF discharge parts and plasma grid etc. The cooling water is supplied from the HVD2 at the inlet temperature of 35 °C and pressure of 2 MPa. The returned water after a heat removal in the beam source is estimated to be at 65 °C. In order to supply such the cooling water to the components at 1 MV, alumina ceramic tube with 500 mm in a length was developed for electrical insulation in the water service line originally. The designed voltage-holding capability was 110 kV for one tube, and 11 tubes connected in series to the 1MV component to sustain 1.2 MV including the margin of 20 %. The actual voltage-holding capability in the room-temperature water was confirmed up to 300 kV for one tube and also pressure tightness up to 3 MPa was confirmed, which satisfied the ITER requirement. However, since risk of break of alumina ceramic tubes during shipping and assembly of more than 70 tubes in total is critical for brittle material, alternative material should be considered.

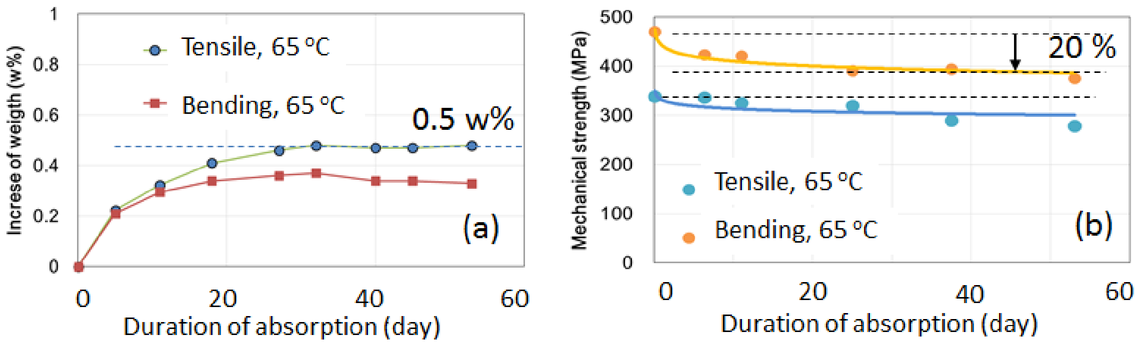

Figure 2 (a) Temporal evolution of water absorption, (b) Mechanical strength of FRP.

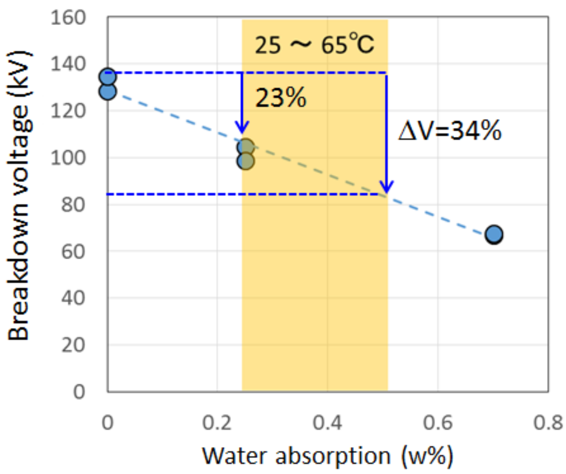

Figure 3 Breakdown voltage of the water-absorbed FRP.

Fiber reinforce plastic (FRP) tube is one of alternatives tanking advantage of mechanical strength, but reduction of the voltage holding capability due to water absorption could be an issue from an electrical point of view. Therefore, variation of the voltage holding capability and the mechanical strength due to the amount of the water absorption were experimentally investigated.

The FRP to be used in the HVD2 should have both sufficient mechanical strength and electrical insulation capability. Therefore, the FRP laminated with the glass cloth and impregnated in vacuum to suppress void in a volume was selected. Test pieces of for tensile and bending test were immersed in water at 65 ^{o}C and the water absorption was measured. Figure 2 (a) shows a temporal evolution of the water absorption in the test piece. The water absorption in the test piece represented by the increase of weight of test piece saturated around 0.5 w%. The tensile and bending strength were measured until the water absorption saturated, and reduction of mechanical strength was found to be around 20 % as shown in Fig. 2 (b).

Breakdown voltage was also measured with water-absorbed FRP tube with inner diameter of 100 mm, thickness of 10 mm and height of 10 mm. Figure GG shows the breakdown voltage as a function of the water absorption. Although the breakdown voltage at typical water-absorbed condition in the HVD2 decreases 34 % compared with FRP w/o water absorption, the breakdown voltage of 10 mm height was still 80 kV as shown in Fig.3. With the FRP tube with 500 mm in height, cooling water can be suppled from the ground to 1 MV potential with 11 FRP tubes each of which is required to sustain 110 kV. Thus, the mock-up of FRP tube with inner diameter of 100 mm and 500 mm in length for cooling water supply was fabricated. Even after the water absorption by filing the water at 2 MPa inside the tube, the absorbed amount of water was found to be 0.25 w% in the actual FRP tube, and also the voltage holding capability of the FRP tube up to 300 kV was experimentally confirmed. Though those development, the cooling water supply system with the FRP tube was established.

3.2. HIGH-TEMPERATURE WATER SUPPLY WITH INSULATING TUBE

Through the water service line from the HVD2, high-temperature water up to 180 ^{o}C is also supplied to the beam source. This high-temperature water is provided to the plasma grid (PG) in the negative ion source to keep its temperature around 150 ^{o}C in order to maintain the enhanced condition of negative ion production on the PG surface. Generally, it is known the water resistivity decreases with increase of the water temperature. Thus, excess self-heating in the high-temperature water service line by a leak current could be a critical issue. In the previous research, the water resistivity was analysed theoretically [13] and measured experimentally [14]. The results in [13, 14] shows the same characteristics as the above general knowledge, however, the resistivity of the typical pure water in the ITER (5 MΩ cm at 25 ^{o}C) does not match the value in [13, 14]. Therefore the resistivity at 180 ^{o}C in the ITER case could not be predicted precisely and consequently the design of the high-temperature water service line could not be confirmed.

Thus, the resistivity of the typical pure water in the ITER was experimentally measured in the identical condition of the ITER NB (2 MPa, 15 L/min at 180 °C). Figure 4 (a) shows the experimental setup for measurement of the electrical resistivity of high-purity water. Temperature of the circulated water was increased with heater up to 180 °C, and then the high-temperature water is supplied to series-connected alumina ceramic tubes. High voltage up to 50 kV was applied to the one tube and the leak current was measured, and then the resistivity at the certain water temperature was obtained from the current-voltage characteristics. The resistivity at several temperatures was obtained using the same procedure by increasing the water temperature. Figure 4 (b) shows the resistivity of high-purity water as a function of water temperature. The resistivity of the typical pure water in the ITER at 180 °C was found to be 0.36 MΩ cm. In this experiment, another high-purity water having the resistivity of 9 MΩ cm at 25 °C was also examined. Although the resistivity of high-purity water at room temperature shows a difference of more than factor of 2 between the present measurement value and the theoretical one, they were found to be almost identical in the temperature region of higher than 100 °C [15].

With the obtained resistivity, a detailed design of high-temperature water channel was

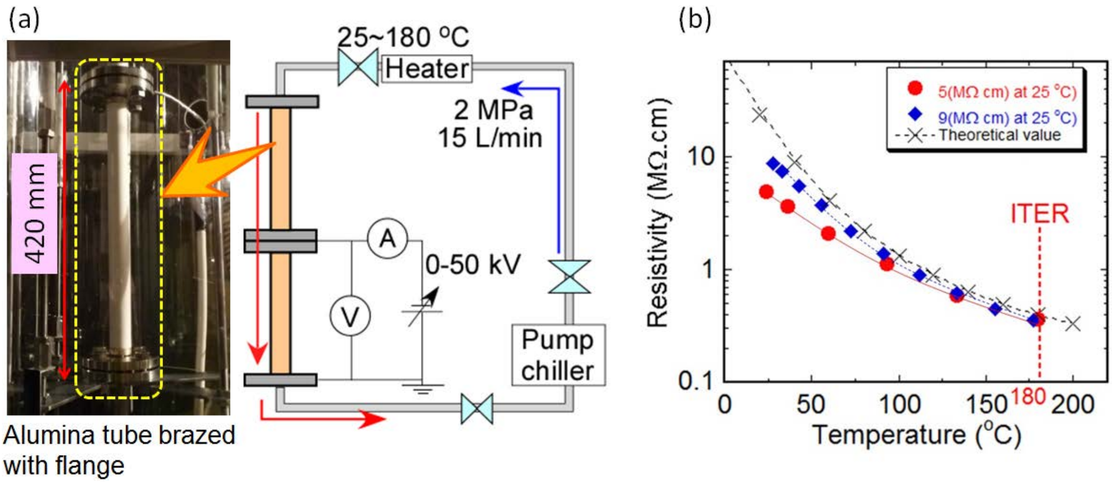

Figure 4 (a) Experimental set up, (b) water resistivity as a function of temperature.

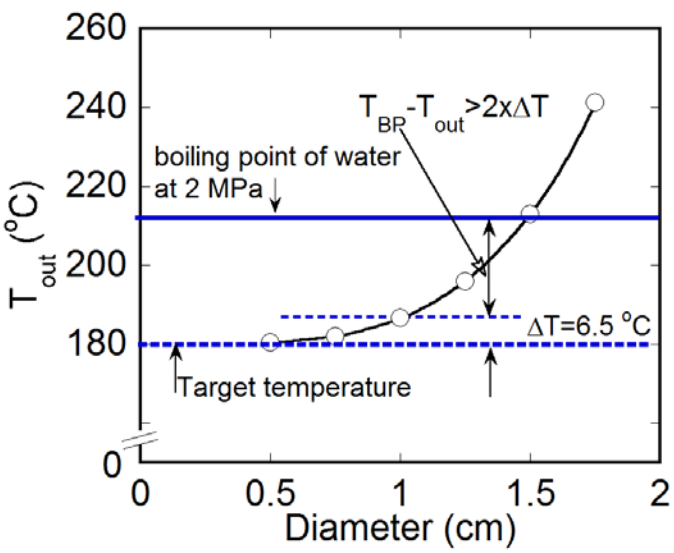

Figure 5 Dependence of outlet temperature of the insulating tube on the inner diameter.

performed. In order to sustain 1 MV at 180 ^oC, number of series connected insulating tubes was selected to be 11, each of which have length of 42 cm taking in account the dimension of the HVD2. For a use of insulating tube at such high temperature, the material is alumina tube. Amount of heat Q due to leak current inside the insulating tube can be expressed as $Q=V^2S/PL$, here V is voltage difference, S is a cross section of insulating tube, P is the resistivity and L is length of the insulating tube. Figure 5 shows dependence of outlet temperature of insulating tube T_{out} on an inner diameter of the insulating tube D_{in}, here the generated heat is assumed to be transfer only to the water, which results in an increase of water temperature. In order to avoid boiling of water, outlet temperature must be less than 210 ^oC at 2 MPa. Also taking into account of manufacturability of the alumina tube and a criterion for temperature increase of $T_{BP} - T_{out} > 2x\Delta T$ in the present case, D_{in} was selected to be 1.0 cm, here T_{BP} and ΔT are the boiling point and temperature increase, respectively. In case of D_{in} of 1.0 cm, ΔT is 6.5 ^oC, which can offer the realistic high-temperature water channel.

Through those development, insulation technologies with oil, gas, vacuum and water have been established and the detailed design of the HVD2 was confirmed. And also the design of the TL3 in which all conductors for electric power and pipes for water and pas concentrate has been concluded through both the electric field analysis and the thermo-mechanical analysis.

4. INSTALLATION OF POWER SUPPLY COMPONENT AND HIGH-VOLTAGE TEST

On the basis of the insulation technology with oil, gas, vacuum insulation, and insulation with

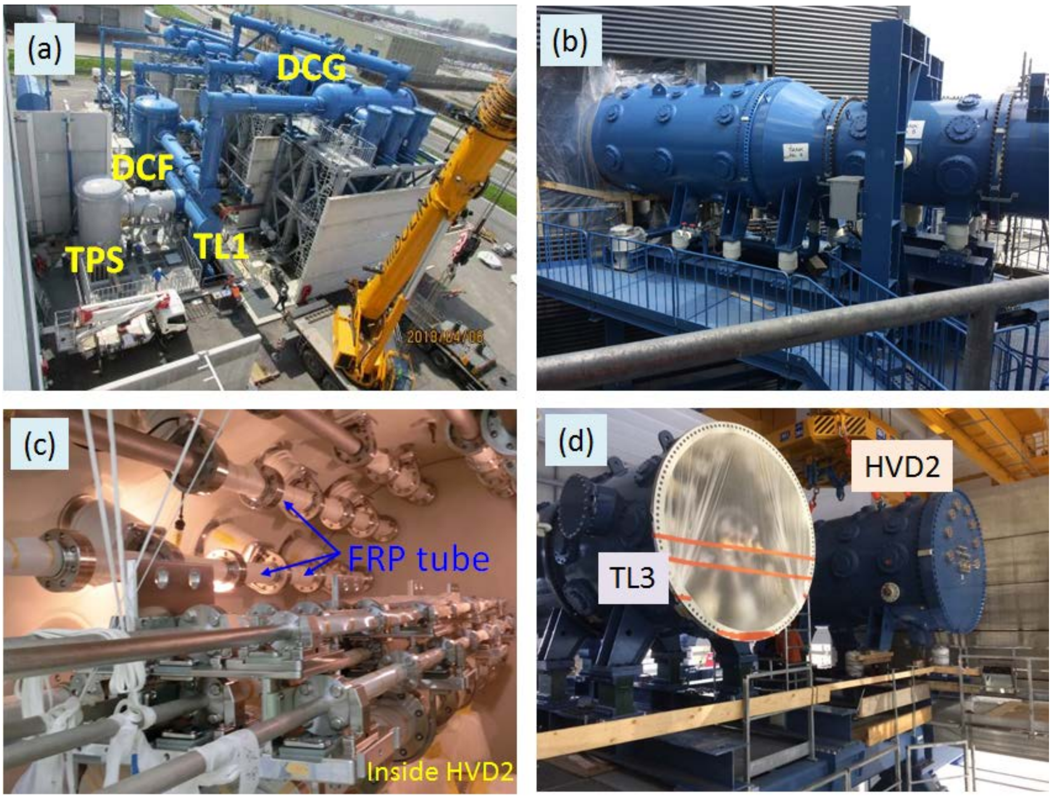

Figure 6 Installation of NBTF/MITICA DC 1 MV power supply components.

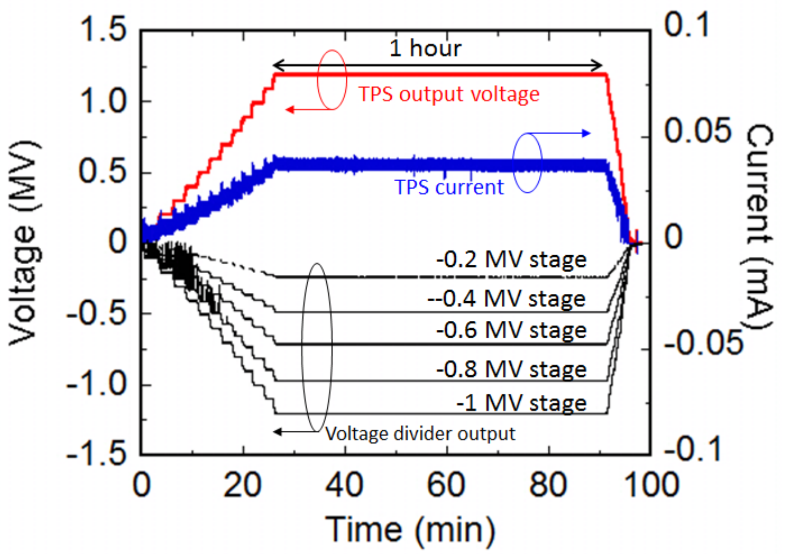

Figure 7 Stable voltage holding in DC generators and DC filter.

water, high-voltage components of DC 1 MV power supply have been manufactured and shipped to the NBTF site. Manufacturing and shipping have been completed by March and October 2017, respectively. In the NBTF site, DC generator was installed outdoor, the TLs consisting of pressurized tanks and internal conductors have been connected from outdoor to indoor penetrating the building wall. The HVD2 with lots of insulating tubes was also installed including the sliding mechanism for the insulating tube to respond the thermal expansion. As for the HV bushing, after the confirmation of 1 MV vacuum insulation capability in Japan [12], the HV bushing was shipped by dividing into the main insulator column and internal conductors and re-assembled on site. The final acceptance test under the witness by the ITER organization successfully completed in the middle of 2017. The HV bushing will be mounted on the vacuum vessel procured by EU and combined with the TL in the near future. Finally, the installation of all Japanese components from DC generators to the TL3 started from November 2015 has been completed by March 2018 as show in Fig.6.

In order to verify the voltage holding capability of the DC 1 MV power supply component, high-voltage test has been started by filling SF6 gas inside the components. As shown in the Fig.1, the total length of the TL is up to 100 m. Only a certain section of the component with length of ~10 m was tested in the factory, hence that was the first trial for the high-voltage apply in the whole assembled configuration. Taking into the risk mitigation, the high-voltage test was planned to do step-by-step for each section. As an initial test, the voltage-holding test of five DC generators and DC filter was examined with the testing power supply (TPS). As a result, voltage holding at DC 1.2 MV with the margin of 20 % for the rated voltage and each intermediate potential for 1 hour was successfully demonstrated as shown Fig.7. In addition to other test condition, voltage holding satisfying the ITER requirement has been confirmed. The voltage holding test in other sections will be continued until 2019.

5. CONCLUSION

Progress on development and construction of the NBTF/MITICA power supply in the last two years was reported. In addition to DC 1MV insulation with oil transformer, with SF6 gas the TL, in vacuum in the HV bushing, the insulation technology with pure water both at normal temperature and high-temperature up to 180 ^{o}C was established. All insulation technologies, namely oil, gas, vacuum insulation, and insulation with water have been established through various R&D in QST. Based on those technologies, manufacturing and shipping of all 1 MV PS components has been completed in 2017. Also, the installation of the component in the NBTF site which started from November 2015 has been completed finally completed in April 2018. As an initial step in a commissioning phase of the NBTF/MITCA project, the high-voltage test of Japanese component (DC generator, TL and 1 MV insulating transformer etc.) has started from September 2018. In the first set of the high-voltage test for five DC generators and DC filter, voltage holding at DC 1.2 MV with the margin of 20 % for the rated voltage and each intermediate potential for 1 hour was successfully demonstrated without any breakdown.

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The views and opinions expressed herein do not necessarily reflect those of the ITER Organization.

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