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Development of Insulator and Liquid Phase Shifter for Long Pulse Operation

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Abstract

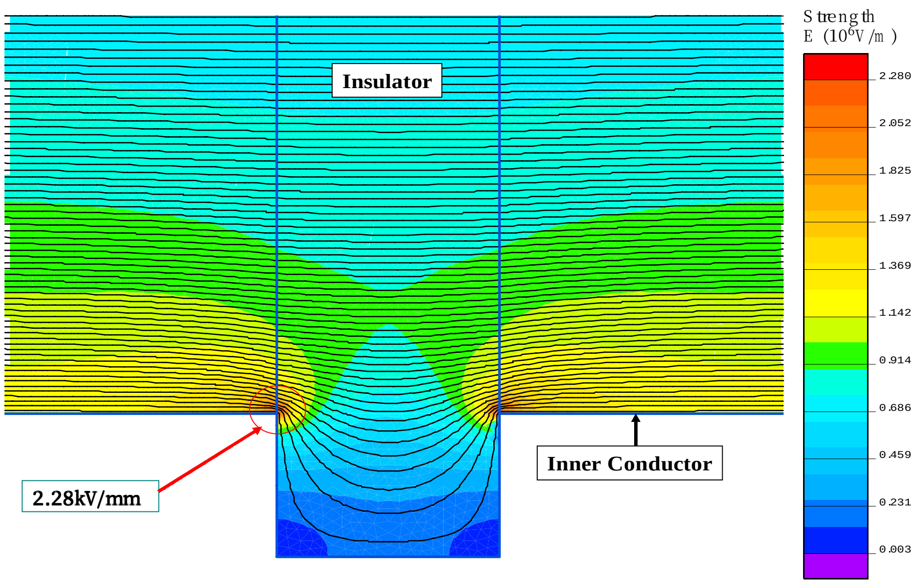
The high power RF transmission components are developed for transmitting MW level of RF power continuously in ICRF heating and current drive system. As an important development of RF components, we have improved a Teflon insulator of the 9-3/16″ coaxial line connected between the antenna and matching components where VSWR is fairly high depending on antenna-plasma coupling. The electric field strength at a point of contact section between point inner conductor and insulator is calculated using the commercial FEM code (Quick Field). We have improved the shape of the Teflon insulator so as to minimize the electric field strength on insulator. A liquid phase shifter is fabricated to replace a conventional phase shifter. The liquid phase shifter uses the difference between RF wave length in liquid and in gas due to the different relative dielectric constant. RF tests show that stable operation is possible with the peak voltage over 48.75 kV for 300 seconds, and they are reliable RF components for long pulse, high power transmission.

1. Introduction

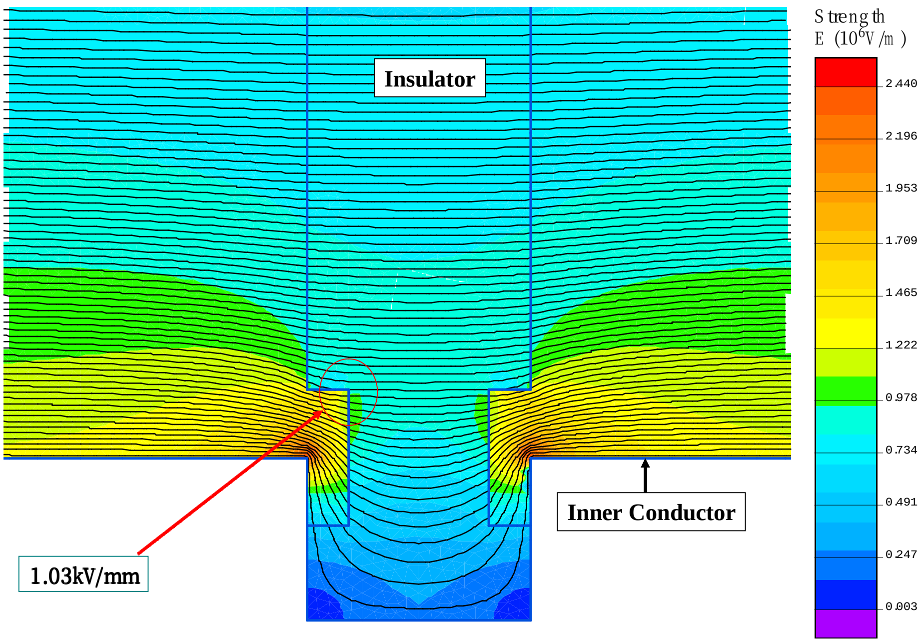
An ion cyclotron range of frequencies (ICRF) system is an important method to heat plasmas and to drive non-inductive current in fusion devices. The high power RF transmission components are required for transmitting MW level of RF power continuously in ICRF heating and current drive system. Key performance required is the maximum voltage and current without breakdown for long pulse operation.[1,2] Steady-state relevant technologies need to be developed in the area of transmission components such as an insulator and the matching devices. To transmit the high RF power (MW level), co-axial transmission line must withstand the high RF voltage (> 35 kV) for a long time.[3] Electric field strength on insulator is calculated and the shape of insulator is designed to minimize electric field strength. Conventional phase shifter has some problem due to difficulties in fabricating straight coaxial line, local temperature increase and insulation breakdown for long pulse operation under high power. To solve such problems, the phase shifter using liquid instead of gas for insulating dielectric medium was developed.[4] The liquid phase shifter can be used reliably in the high power continuous RF facilities since it has no sliding contact and can withstand the high RF voltage (> 40 kV). A liquid phase shifter made of 9-3/16″ nominal diameter aluminum transmission line was developed. The results of the developments will make ICRF system a key element for the steady-state, high performance operation of fusion devices.

2. Development of Insulator for High Voltage

As an important development of RF components, we have improved a Teflon insulator of the 9-3/16″ coaxial line connected between the antenna and matching components where VSWR is fairly high depending on antenna-plasma coupling resistance. The required design value of stand-off voltage for the insulator is about 35 kV at the maximum rating of 1.5 MW injection. Breakdown occurs for a conventional disk insulator at high RF voltage. The traces of the breakdown are seen near the contact section of the Teflon insulator with the radial surface of the inner conductor undercut.[5] To minimize the electric field strength on insulator, the new shape of insulator is designed. The electric field strength is calculated at the contact point inner conductor and insulator using the commercial FEM code (Quick Field). It is found from the calculation of the static electric field shown in fig. 1(a) that the maximum electric field is generated at the contact section where the dielectric materials contact with the conductive materials at small acute angle. In the case of a voltage difference of 50 kV between inner and outer conductors, electric field strength at a point of contact section between inner conductor and insulator is 2.28 kV/mm for insulator which is not undercut. Therefore, we have improved the shape of the Teflon insulator so as to contact with the radial surface of the undercut at right angles. After insulator is modified with undercut, electric field strength at the area of inner conductor is 1.03 kV/mm. The maximum electric field generated in the modified insulator decreases to less than a half of that in the conventional insulator as shown in fig. 1(b).



(a)



(b)

Fig. 1. Distribution of the calculated static electric field on a half cross section of a coaxial line applied by 50 kV between the inner and outer conductors with a conventional Teflon insulator(a), and a modified Teflon insulator(b)

Table 1 shows the maximum electric field strength on various shaped insulators. The unit of electric field strength in Table 1 is kV/mm.

Table 1. Calculated electric field strength (kV/mm) on various shaped insulator with an applied voltage of 50 kV between the inner and outer conductors

Width(mm) / Depth(mm)	0	4	6	8	10	12
0	2.28					
1		1.24	1.24	1.23	1.22	1.22
2		1.24	1.12	1.11	1.10	1.08
3		1.28	1.16	1.07	1.03	1.05
4		1.31	1.19	1.10	1.02	1.03
5		1.33	1.21	1.12	1.04	1.03

From the data of electric field strength on insulator with undercut, we fabricated insulator with 3mm depth and 10mm width undercut. Figure 2 shows assembly of modified insulator and anchor connector.

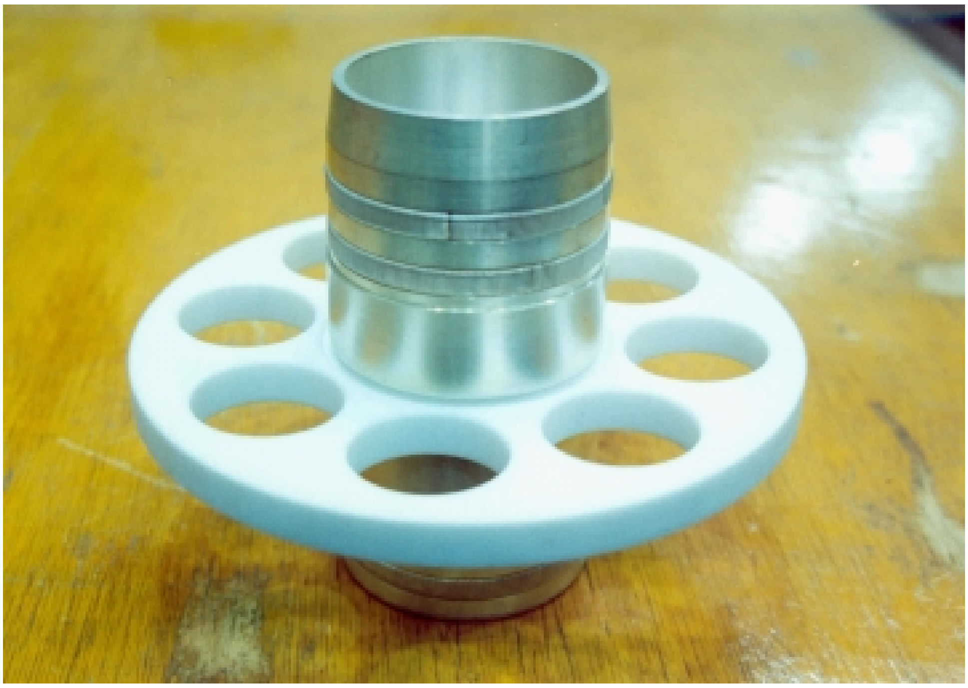


Fig. 2. Assembly of modified Teflon insulator and anchor connector

3. Development of Liquid Phase Shifter

The liquid phase shifter contains a liquid between inner and outer conductors of coaxial transmission line. By changing the liquid level instead of shifting the electric short-end, the phase of the wave can be shifted based on the difference between RF wavelength in liquid and in gas due to the difference relative dielectric constant. It is dangerous to move the sliding joint of the conventional phase shifter during high power ICRF heating, because 1 kA of RF current flows there in MW level heating. Therefore the liquid phase shifter will be superior to conventional ones. The liquid phase shifter was made of 9-3/16″ nominal diameter aluminum transmission line. Two identical 3m long liquid phase shifters are connected with U shaped 1.6m spacing elbow, and two separating disks of Teflon at top and bottom of liquid phase shifter were inserted to stop the diffusion of vaporized oil to the other part of transmission as shown in Fig. 3. Silicon oil with the relative dielectric constant of 2.74 is used as a liquid. It was selected because of the low vapor pressure and low dielectric loss. The vapor pressure is less than 0.1torr even at 240 ℃. The dielectric constant, ε_r is 2.74 and the dielectric loss tangent, tanδ is 10^{-4} to 3.3 x 10^{-4} in the frequency range of 10 ~ 100MHz at 25 ℃ as shown in Table. 2. Asterisk in Table 2 mean that the data are available when silicon oil contains under 50 ppm water. The speed of motion of the liquid surface is 1.8 cm/sec. The liquid phase shifter is equipped with electrostatic probes to measure RF voltage and two thermocouples for the liquid temperature and a humidity sensor to measure humidity in the coaxial transmission line. The schematic diagram of co-axial transmission line test with liquid phase shifter is shown in Fig. 3.

Table 2. Characteristics of silicon oil (Dimethyl Polysiloxane)

Specific Gravity (25°C)	0.965
Viscosity (25°C)	100 mm^2/s
Vapor Pressure (<260°C)	<0.1mHg
Specific Heat (25°C)	0.36cal/g·°C
Thermal Conductivity (25°C)	3.8×10^{-4}cal/cm·sec·°C
Resistivity*	> 1×10^{14} Ω·cm
Dielectric Strength*	> 50kV/2.5mm
Dielectric Constant (50Hz)*	2.74
Dielectric Loss (tan δ)*	< 0.0001
* mean in Table 2 : Water <50ppm	

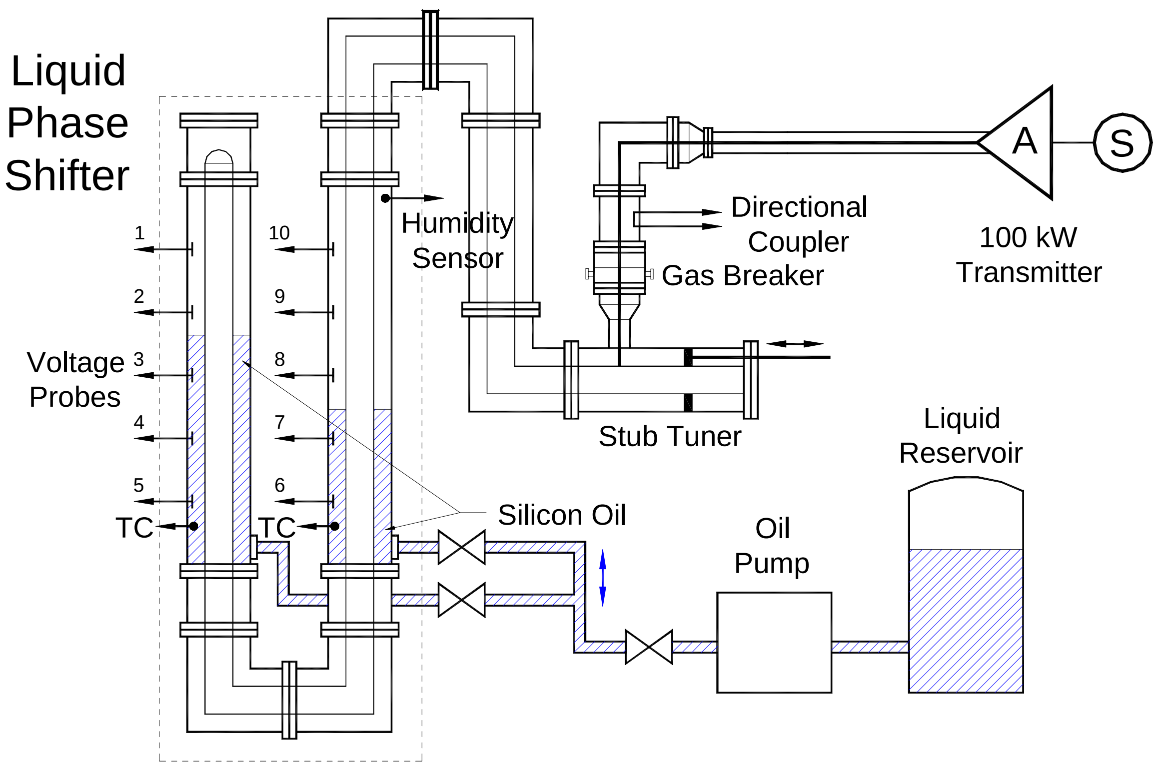


Fig. 3. High power RF test stand schematic

As liquid level is raised from 0 m to 5.6 m, the phase angle varies from -120° to 10° (equivalent line length variation of 3.6m).[6] Voltage probes are fabricated and calibrated with applying low RF power. Measured voltages and calculated voltage curve are shown in Fig. 4 at the frequency 30 MHz. The open circles denote measured voltages and the solid line presents calculated voltage distribution.

4. High Power RF Test

The RF power test of the liquid phase shifter was accomplished at f = 30MHz using the experimental apparatus shown schematically in Fig. 3. Liquid phase shifter is connected to the pressurized transmission line and short stub tuner. The matched line section from stub tuner to liquid phase shifter is pressurized with N_2 gas at 3kgf/cm^2 to increase stand-off voltage. The matching circuit is connected to the RF transmitter through the dual directional coupler. During the RF pulse, temperatures of the liquid were measured by 2 thermo-couples and the temperature of the outer conductor of liquid phase shifter was measured by equipped thermo-couple. The line voltages, forward and reflected powers were also measured. Figure 5 shows the RF voltage and current distribution from liquid phase shifter to short stub tuner when RF power of 6 kW was applied for 300sec at 30 MHz. The zero position is at the opened end. The maximum voltage at the boundary of liquid and gas exceeds 48.75 kV. The maximum current in liquid region was higher than 1 kA. Time evolutions of RF pulse, the line voltage, the temperature are shown in Fig. 6. The average voltage of the standing wave was 48.75 kV during 300second and temperature increase of outer conductor of liquid phase shifter was up to 35 ℃ (T_o = 26.5 ℃). The RF voltage of 48.75 kV is equivalent to a 2.85MW transmission power to the antenna with 6 Ω/m of expected plasma loading.

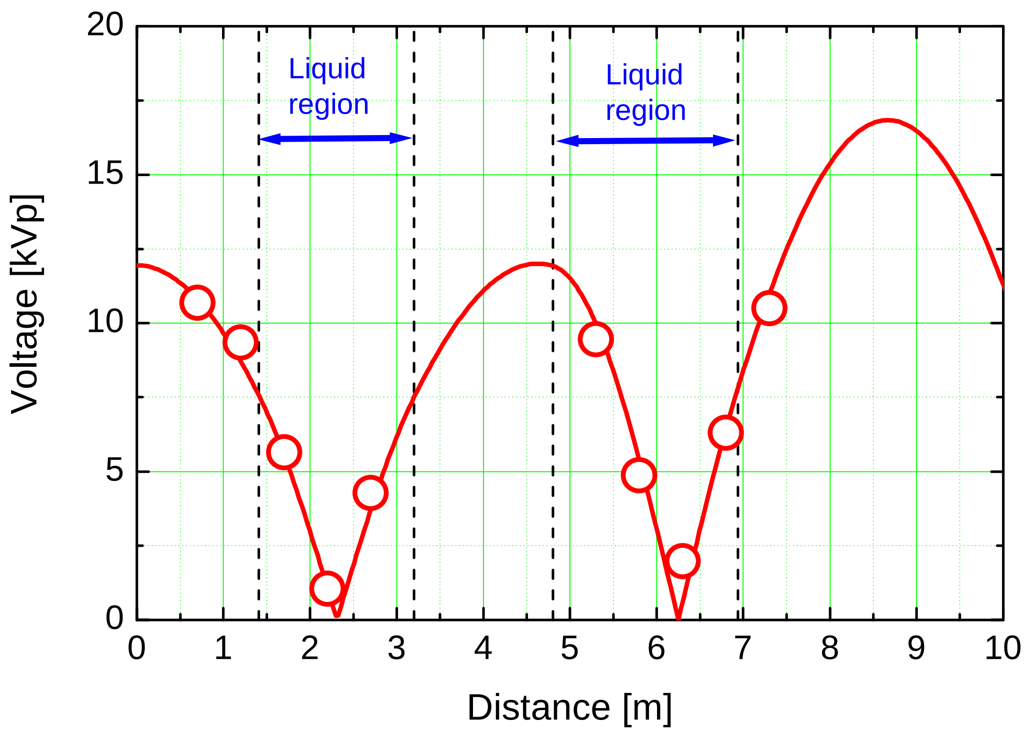


Fig. 4. Voltage distribution along the of the liquid phase shifter with low power

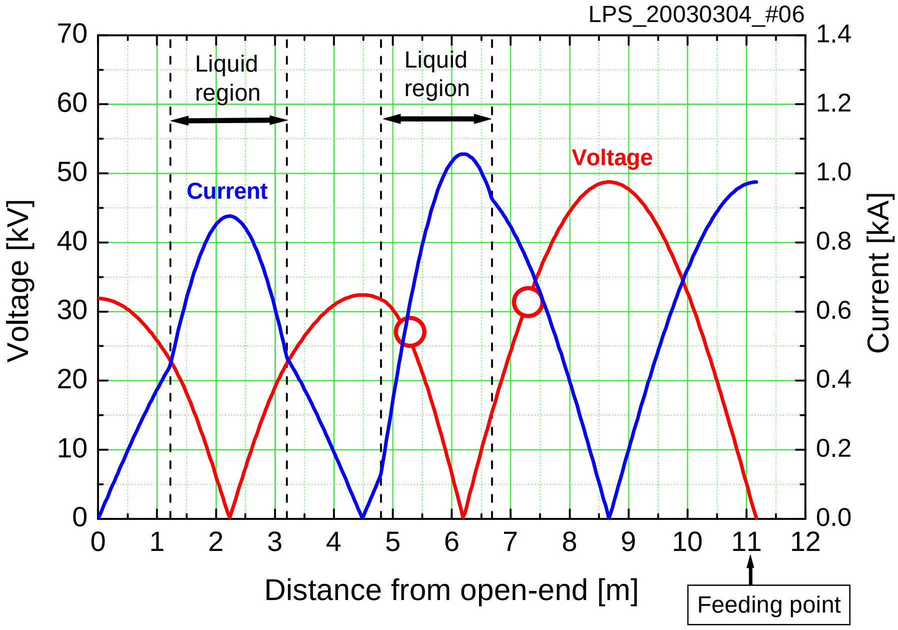


Fig. 5. Voltage and current distribution of the liquid phase shifter.

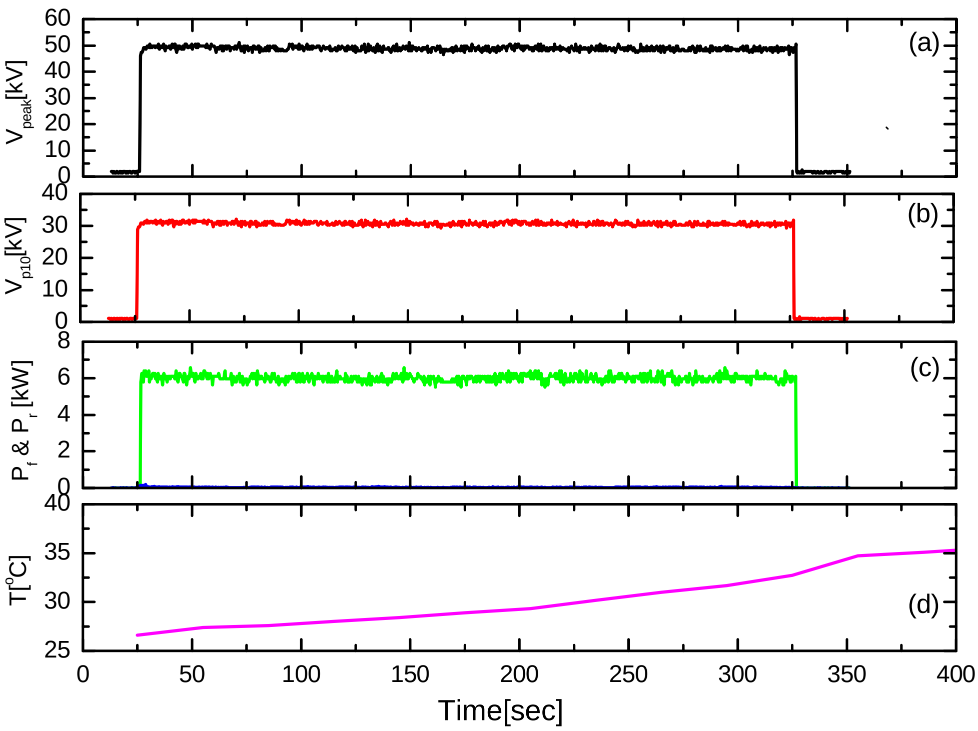


Fig. 6. Time evolution of peak voltage (a), line voltage at V-probe (b), forward and reflected power (c), and temperature of coaxial outer conductor (d).

5. Summary

The high power RF transmission components were designed and fabricated for KSTAR ICRF system. The maximum electric field generated in the modified insulator decreases to less than a half of that in the conventional insulator. The RF power test of the liquid phase shifter was performed at f = 30 MHz; stand-off voltage of 48.75 kV(average) at a long pulse of 300 second. It is confirmed that RF components can be satisfactorily used for long pulse, high power transmission.

Acknowledgements

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