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DESIGN AND CHALLENGE FOR ITER DIVERTOR LANGMUIR PROBE

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Abstract

The ITER divertor Langmuir Probe system is aim to measure the plasma parameters, including electron temperature, density and ion flux at the divertor target plates. These measurements will be used for ITER advanced machine control, as well as physics studies. Now the ITER divertor Langmuir probe system is in the final design stage, some main components design almost finished and have entered the testing phase: 1) For probe sensor, the tungsten sensor structure has been already determined and the manufacture technique also has been developed, tens of prototypes was produced and used in a series of test, such as ITER-like high heat load thermal cycling test and tokamak plasma test, and they shows very positive results. 2) The all-in-one power supply, which integrated the power supply, mode switching and signal conditioning functions, was design for space saving. And it was test in many magnetic confinement devices with good results. 3) The function design of instrumentation and control (I&C) system is ongoing, including the publishing configuration, monitoring and control, calibration, data acquisition, communication with the control, data access & communication (CODAC) system. As the schedule, the ITER divertor Langmuir probe final design is doing continuous optimization with the tests results and the final design review will be in the end of 2025.

1. INTRODUCTION

The ITER divertor Langmuir probe (DLP) system is one of the key diagnostics of ITER[1,2], which is the biggest magnetic confinement fusion device the world over for scientific and engineering research and perhaps the most challenging scientific endeavour being undertaken today. The DLP system is aim to measure the profiles of plasma parameters on the divertor, to supply key data for ITER advanced machine control and physics studies.

The Langmuir probe, or electrostatic probe, was developed by Irving Langmuir in the 1920s, The principle is relatively simple: a conductor in contact with the plasma is biased with a voltage relative V to the local plasma potential. The current I drawn by the probe is proportional to the local plasma density n and temperature T: $I \propto ne^{V/T}$. But in practice, the analysis of probe data is more complicated, especially in the presence of magnetic field. It involves many other parameters, such as the shape of probe, the angle of magnetic field, Debye sheath, the particle cyclotron radius, the secondary electron emission, and so on.

Divertor Langmuir probe have been successfully implemented in nearly every tokamak in the world, such as JET[3], JT60-SA[4], DIII-D[5],and provided a large amount of critical data for these devices. They are always use to measure the electron temperature, density and ion flux of divertor, to help the tokamak to understand and control the divertor configuration discharge, to recognize and study detached/attached state, and to do physics research on plasma confinement, such as heat/particle redistribution and impurity transport. These are as well as ITER DLP's main purpose for its tungsten divertor[6], The requirements of DLP are defined and summarized in Table I

TABLE 1. MEASUREMENT REQUIREMENTS FROM MEMORANDUMS AND ANNEX B

Measurement	Parameter	Operational Role	Range	Time resolution	Spatial resolution	Accuracy
Plasma Parameters at the divertor target	Γi, Divertor ion flux	Advanced control	10^5 to10^7A/m^2	10 ms	12 mm	10% relative
Plasma Parameters at the divertor target	n_e, divertor target	Physics	10^{18} to10^{22} m^{-3}	1 ms	12 mm	30%
	T_e, divertor target		1 to 50 eV	1 ms		
	Γi, Divertor ion flux		10^5 to10^7 A/m^2	10 μs		

Though the DLP function is similar with many other divertor probe system of existing/decommission tokamak, as it is the diagnostic of first fusion reactor in the world, we need to solve many technological problems, some of them are critical ones:

The first one is high heat load problem. Due to the giant heating power and fusion power, the DLP sensor should suffer huge heat load, which comes from plasma flux, photon irradiation, and energetic neutrals from charge exchange reactions. The SOLPS simulation shows that the heat load can reach up to about 15MW/m^2 at strike point[7]. By considering a more conservative estimation, DLP has to choose 18MW/m^2 with 10s exposure[8] as the typically maximum heat load for DLP design, with similar requirement of ITER divertor.

The second one is the dust deposition which can destroy the insulativity of probe. Though this problem also happens in many other tokamaks, as a semipermanent component welded on the ITER divertor cassette, the DLP sensor cannot be maintained like other tokamak. we need to protect DLP sensor from deposition affect as long as possible.

2. ITER DIVERTOR LANGMUIR PROBE SYSTEM DESIGN

The DLP [9] sensors are distributed on five ITER divertor cassettes, Total 400 sensors will be attached to the sides of the inner and outer target of ITER divertor, and with corresponding signal wires. The electronics equipment, which are 200 all-in-one power supplies and corresponding I&C equipment installed in total 30 cubicles, will be in ITER diagnostic building. They provide function such as voltage/current drive capability, probe signal measurement, ground potential measurement for different ITER ground, signal acquirement and upload, system control and communication, and cubical status monitor.

In DLP system, the probe working mode can be switch in the one of three types after discharge: 1) Single-probe voltage sweep mode, to measure the single probe I-V characteristic with maximum frequency of 1kHz; 2) Double-probe voltage sweep mode, to measure the double probe I-V characteristic with maximum frequency of 1kHz; 3) Single-probe DC mode, to measure the saturated ion current. In all these modes the maximum voltage and current derived by all-in-one power supply are ±150 (-150 for DC mode) and 1A.

2.1. Probe Sensor

2.1.1. Probe sensor design and prototype

The probe sensor is designed as a full tungsten structure with a thin aluminium oxide insulator inside and as figure 1 shows. The main body of the tip is 3mm in diameter and total 25mm in length made by pure tungsten. Meanwhile there is a step-like special structure in the top of tip, the diameter becomes 2mm and the length is 5mm in 25mm. the tip will be applied with potential to collect ion and electron to measure the plasma density and temperature. The heat shield is irregular structure, also made by pure tungsten, acting as a protection used to absorb the external heat. The top of the shield is flush with the tip, and the bottom protruding structure of shield is used to fix the installation location to the ITER divertor monoblock. Between the tip and heat shield there is a very thin aluminium oxide insulator. Although the insulator thickness is only about 0.4~0.5 mm, a small step-like structure is designed on its surface, reducing the minimum thickness to ~0.2 mm. The probe sensor will be bonding on the side of monoblock, and the top of sensor is design ~0.3mm lower than the top of monoblock, in order to protect the adjacent components (monoblocks or other diagnostic components) from the probable penetrating ions.

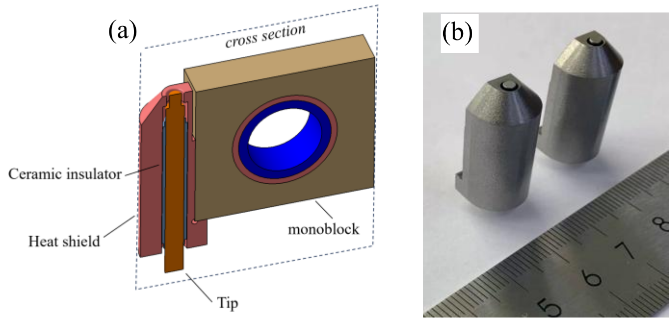

Figure 1 (a) the design of DLP sensor bonding with monoblock and (b) the prototype of sensor

Consider ITER high heat load and complex environment, there are some advantages in the current design: First, the 3mm tip main body create batter vertical thermal conduction capacity, which is conducive to the reduction of the temperature of the tip head; Second, the thin aluminium oxide insulator which is welded to the tungsten tip and heat shield, provides acceptable horizontal thermal conductivity and electrical insulation. Third, step-like structure in tip and insulator is used to protect the electrical insulation from plasma coating and dust.

The thermal and mechanical properties of probe sensor was analysis [10] in ITER detach and attach case with maximum total thermal load 10MW/m^2 and 18MW/m^2 respectively. The maximum values of all components (always in the top) are show in table 2.

TABLE 2. THE THERMAL AND MECHANICAL RESULTS OF PROBE SENSOR IN ITER OPERATION

Component	Max Temperature(°C)		Max Stress (MP)	
	Detach	Attach	Detach	Attach
Tip	1113.8	1750.4	304.01	433.00
Insulator	637.4	755.55	173.66	116.74
Shield	1312.1	1578.8	446.62	605.28

The Xia Men Tungsten Company, Ltd., China (XTC) joined the development of the sensor manufacture technique, including machining, sintering, and brazing. The sensor prototype shows in figure 1(b). Then Two critical tests were done for verification of the problems mentioned in the introduction of this article: high heat load thermal cycling test and long plus plasma test.

2.1.2. High heat load thermal cycling test

High heat load thermal cycling test is force on the probe sensor high heat load withstand capability. The primary concern is the variation of sensors' temperature during test, the external structure after test, and the most important, the electrical resistance between tip and shield which can affect the probe measurement directly in ITER. The test was conducted on an electron beam facility EMS-60 [11], which can offer maximum 20MW/m^2 heat load with heating duration more than 100s. Three standard ITER DLP sensor prototypes were welded on the cooling module as shown in fig 2(a), which are similar with sensors welded on ITER monoblack, and install in the electron beam facility. The prototypes were sequentially exposed to 3 kinds of electron beam heating: i) 300 cycles of 20MW/m^2 with 10s plus, ii) 100 minutes steady state of 10MW/m^2, and iii) 5000 cycles of 10MW/m^2.

In the test, the temperature of the sensors, measured by colorimetric thermometer, stabilized in 5s after electron beam heating, which is shorter than the plus duration 10s. The maximum value of temperature was in the top of tips and did not change much during the test. The maximum temperature is ~920℃ in 10MW/m^2 case and 1760℃ in 20MW/m^2 case, which is closed to the thermal analysis results [10].

The electrical resistances were measured by resistance meter in the voltage 150V, which is DLP operation voltage in ITER. Figure 2(b) shows the resistance evolution of 3 sensors during the test. It shows that the original resistances of sensors are several GΩ and the welding decreased the them. The minimum/maximum value is ~60MΩ/3GΩ. After 300 cycles of 20MW/m^2 thermal load test, the minimum/maximum resistance was ~90MΩ/750MΩ. After 100 minutes steady state of 10MW/m^2 thermal load test, the resistances decreased significantly to ~1MΩ/30MΩ. At last, after 5000 cycles of 10MW/m^2 thermal load test, the resistance had a slight recovery to ~3MΩ/120MΩ. Though the electrical resistance of these sensors has been dropped, the 3MΩ still can meets the ITER measurement requirement because the leakage current of probe is only ~ 50μA in 150V probe bias voltage. At last, there is not any external structure damage or deformation during the test.

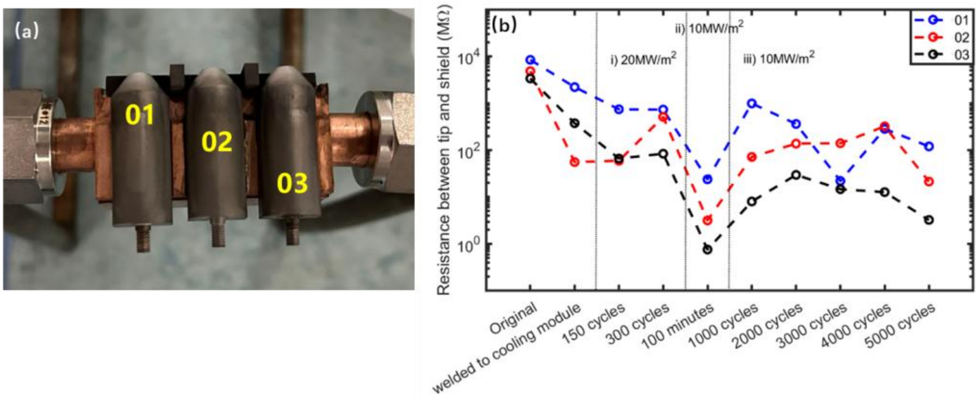

Figure 2 (a) the sensor prototypes in electron beam test and (b) the resistance evolutions of 3 DLP sensors during the test

2.1.3. Long plus plasma test

Long plus plasma test is force on the signal verification and dust deposition effect. As the limitation of the installation space, 6 special sensor prototypes were test in EAST tokamak [12] which is a low temperature superconducting tokamak with discharge duration from tens of second to thousands of seconds. These special sensor prototypes feature the same tungsten tip and ceramic insulator configuration as the ITER DLP sensor, but the tungsten heat shield is different. The special sensor prototypes were installed in the lower vertical divertor target of EAST, 2 prototypes in inner target and 4 in outer target, as figure 3(a) and 3(d) show. 6 EAST conventional divertor carbon probes were installed closed to the special sensor prototypes to compare the measurement signal. Total ~90,000 seconds discharge was done for the test. And it's worth noting that several boronization experiment, which is also ITER wall conditioning techniques, were done in EAST during the campaign. It provides this test with conditions closer to ITER operation.

In the test, the ion saturation measured by special sensor prototypes and EAST carbon probes are matches very well, which shows in figure 3(d) and 3(c) as examples. The resistances of sensors was measured outside EAST between the signal wire and outer wall of EAST vacuum chamber, which is the probe ground electrode. During the test, we found that the resistance of all 6 special sensor prototypes decreased. 3 prototypes' resistances were less than 1MΩ (prototype number: 3-1, 4-1, 1-1) after the test, while other 3 resistances remained in the region 5~20 MΩ (prototype number: 1-2, 2-1, 2-2). Unfortunately, the surfaces of sensors were contaminated before we remove them from divertor, and the energy dispersive spectroscopy can not detect the top surface of ceramic layer due to the thin and complex gap between tip and heat shield. We can not analysis element inside the gap. But after a simple ultrasonic cleaning, all sensors returned to MΩ-level resistance implying that the dust played a role in the test. As ITER DLP can not be repair after installation, an optimized design and a possible resistance recovery method was proposed and will be discussed in the conclusion section.

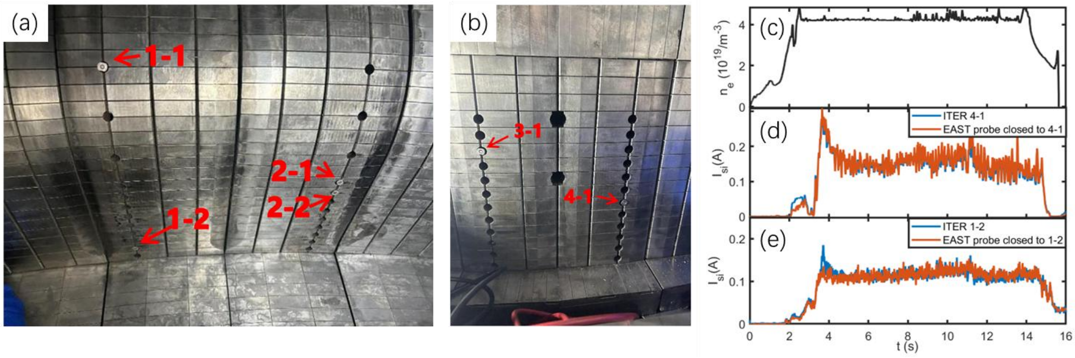

Figure 3 the installation of prototypes in EAST (a) lower outer vetical divertor target (prototype number: 1-1,1-2,2-1,2-2) and (b) inner vertical divertor target (prototype number: 3-1,4-1). (c) is the evolution of average density in a typical EAST discharge. (d) and (e) are the singnal comparaions between ITER prototypes and EAST probes

2.2. Power supply and signal measurement

2.2.1. All-in-one power supply

The All-in-one power supply system for the DLP system was specifically developed for ITER. The basic properties comes from ITER requirement: 1) The current and voltage of the power supply output are 1A and 150V, respectively; 2) The power supply can be remotely controlled and communicate with the fast controller; 3) The power supply bandwidth can be from DC to 10 kHz, ensuring good DC bias, sweeping wave, and quick responding with four quadrants operation capability; 4) Each power supply drives two probes, and can configures the probe working modes; 5) The probe signal measurement circuit is integrated into the power supply unit; 6) The power supply is small with high efficiency, and the height is less than 2 U.

The main power amplification module, shown in figure 4(a), includes the main power amplifier group H and the main power amplifier group L. They are two symmetrical power amplification circuits. The power amplifier in Group H uses the isolated in-phase signal, while the one in Group L uses the isolated inverted signal, For group H power amplifiers, the input signal is ±7.5V, and after in-phase power amplification, the output voltage is+/-75V. For group L power amplifiers, the input signal is ±7.5V, and after inverting power amplification, the output voltage is -/+75V. After the symmetrical two sets of power amplifier circuits are combined, the output voltage is ±150V, and the overall amplification factor of the main power amplifier module is 20 times.

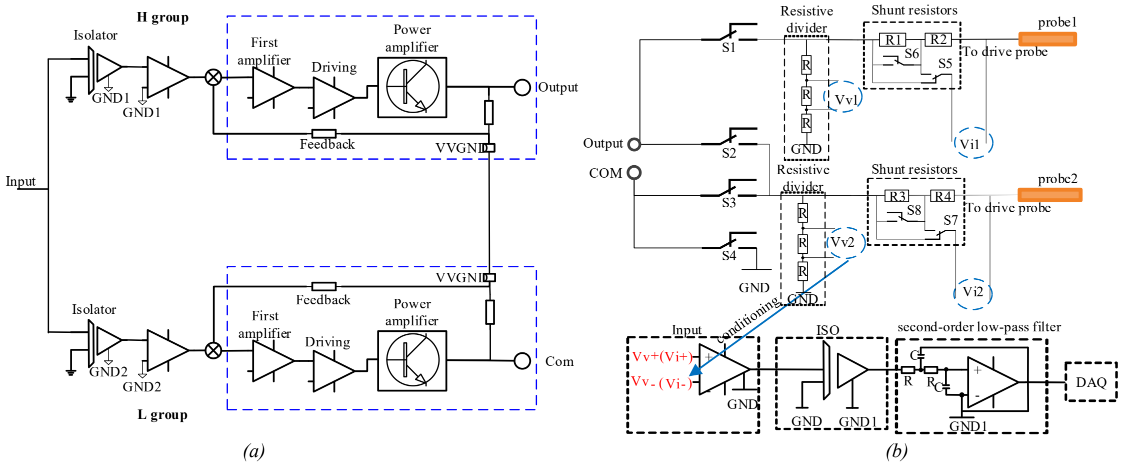

Figure 4 Topology diagram of (a) the main circuit and (b) the switching and conditioning circuit.

Figure 4(b) is a simplified schematic diagram of the switching and conditioning circuit. The upper part involves the switching of the probe working mode and the switching of the current sampling resistors. The cooperation of relays S1 - S4 enables the switching between single - probe and double - probe modes. The cooperation of relays S5 - S8 enables the switching between large and small resistors. The lower part is the signal conditioning channel, which isolates and amplify the two measured voltage signals and two measured current signals. The all-in-one power supply was already tested in the leaner device LEAD [13], tokamak HL-2A [14], HL-3[15], EAST [12], Stellarator CFQS [16] and showed excellent operational performance.

2.2.2. Ground potential measurement

As the ITER Langmuir probes are installed on divertor targets in the vacuum vessel, they are far from the diagnostic area (cable length 150m~100m), which is the location of the back-end electronics. In order to interpret the probe signal, the measured probe potential must refer to the nominal plasma ground. It is not easy to do, especially in plasmas with significant noise. Commonly, the reference of the probes may be the local tokamak metal surface near the probes or the building ground of the power supply. In order to add flexibility, several grounds are proposed at the divertor cassette: Three grounds are on the inner, outer, and centre of the cassette, and another one is close to the cassette attachment point to the vacuum vessel. These grounds are to be viewed as signals and will not be tied to the local ground at the location of the electronics. A special measurement equipment is developed to record the potential evolution of these grounds during discharge. It will help us to determined which ground will be the better reference ground potential for the DLP system

2.3. Instrumentation and Control

The ITER Langmuir probe system, like other diagnostic systems, is to be a plant system to the ITER control, data access and communication (CODAC) system to allow ITER operators to remotely access and control it. The system includes several functions: communication, data acquisition, configuration publishing, and various monitoring and control functions.

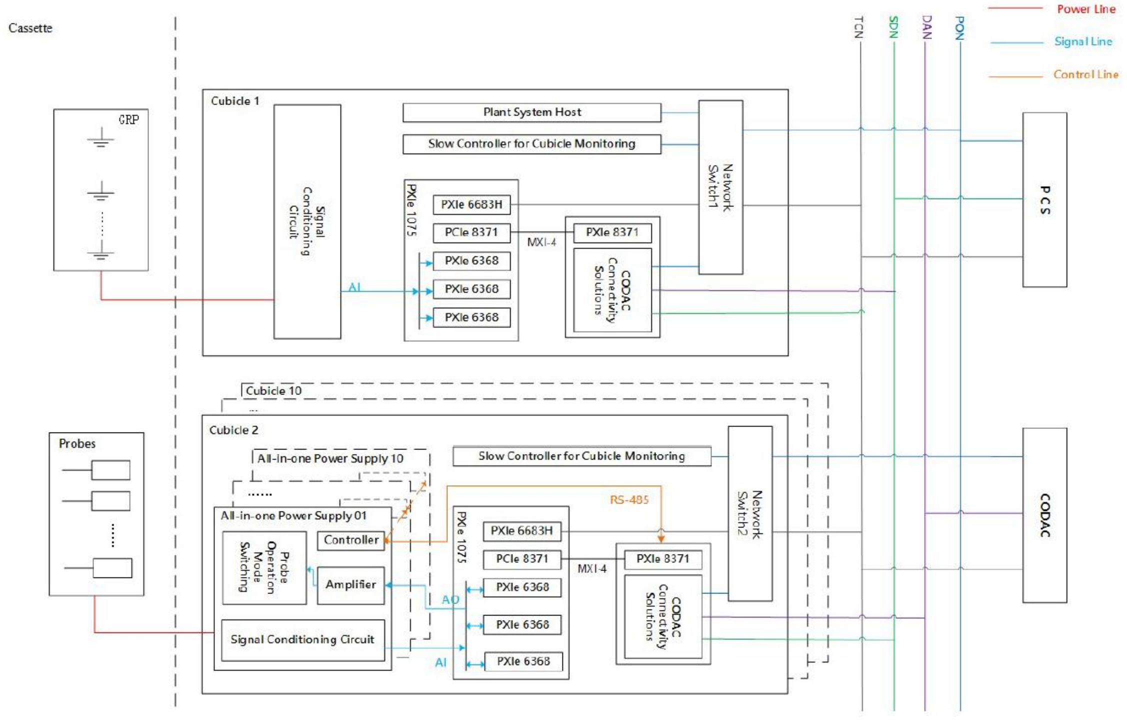

Figure 5 DLP I&C architecture

The main operational interfaces for the 55.G7 DLP diagnostic are given in Figure 7. The 2 direct operational interfaces are with PBS 43 (through PBS 55.NE.X0) for the electrical power and with PBS 45 CODAC for the exchange of data with other systems. For DLP system, normal Class IV-OL power is used. Direct interfaces with CODAC arise because of the need to host processing software for the calculation requirement measurement parameters, as well as the requirement for complimentary parameters to be delivered by CODAC for these calculations. Interface with PBS 47 Plasma Control System arises due to the role of the Langmuir Probe system as the primary diagnostic for delivering the Ion Flux at the Divertor Target for Advanced Machine Control. This interface is functional, in that the Probes provide the estimate to CODAC and CODAC will have the direct interface to PCS. Thus, this interface is transferred to PBS 45.

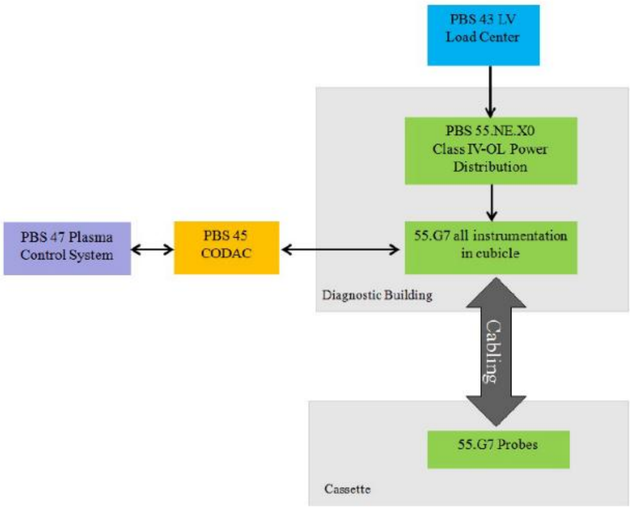

Figure 6 operational interfaces

3. DISCUSSION AND CONCLUSION

The ITER divertor Langmuir probe system consists of Langmuir probes sensor, all-in-one power supply, and instrumentation and control (I&C) systems, designed for advanced machine control and physical research. The probe sensor is made by a tungsten probe body, insulating ceramic, and a specially shaped tungsten shield. These components are integrated using a specialized welding process developed by XTC Company, ensuring efficient heat conduction from the probe to the divertor monoblock. Both high heat load thermal cycling tests and long pulse plasma tests were done for the probe sensor, to demonstrate their operational reliability under ITER conditions.

All backend electronic equipment is housed in diagnostic area cabinets. The all-in-one power supply system features four-quadrant operation and high bandwidth characteristics, meeting the operational requirements for both recommended DC bias mode and swept single/double-probe mode while integrating probe signal measurement capabilities. This power supply has been extensively tested on multiple magnetic confinement plasma devices with excellent results. The I&C system incorporates multiple functions including communication, data acquisition, configuration publishing, and various monitoring capabilities. The fast controller transmits control waveforms to amplifiers for probe actuation while simultaneously acquiring analog signals at 100 kHz sampling rate via MSSCB to derive current-voltage (I-V) characteristics.

Now the only left critical issue is the dust effect found in the EAST test. A preliminary medication design is considered. In this design, the diameter of the tip's main body increases from 3mm to 4mm, while the tip center moves outside (away monoblock direction) 1mm. The top area of heat shield will extend to the same direction and increase correspondingly. That will increase the heat load of heat shield and make its temperature higher. But as the main body of tip increases, the tip temperature reduces obviously. And it can give us an opportunity to decrease the height of ceramic layer, making the surface of ceramic away the top of gap and plasma to reduce the dust effect. Meanwhile, a method involving the application of transient current to the probes to restore their insulation performance is also under consideration, with preliminary experimental tests currently being conducted.

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