Robust Langmuir probe circuitry for fusion research

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Langmuir probes attached to the plasma facing components of fusion experiments are biased with constant or swept voltages to obtain measurements of plasma parameters such as electron temperature and density. The circuitry used must be rugged and protect the power supplies and electronics against generally harsh conditions and sudden discharge terminations, or disruptions. Modularity, ease of repair and expandability are important because short-lived radiation from neutron activation is often present after the discharges, preventing access to the circuitry. We report the implementation of modular probe circuitry featuring robust protection, remote testing and reset and easy maintenance and expandability, achieved by using DIN-rail modules. [DOI: 10.1063/1.1340023]

I. INTRODUCTION

Langmuir probes fixed to the surface of plasma facing components are widely used in tokamak fusion experiments to evaluate plasma parameters in the edge and scrape-off layer (SOL), provide input to modeling codes,[1] aid in studies of particle exhaust[2,3] and impurity transport[4] and evaluate plasma damage to plasma facing components (PFCs).[5] The Advanced Limiter Test II (ALT-II) system,[6] shown in Fig. 1, is a pump limiter consisting of a toroidal belt made of eight identical sections or blades and ancillary systems that was designed to provide power and particle control for the Torus Experiment for Technology Oriented Research (TEXTOR). Particle control[7,8] is achieved by channeling the SOL plasma into a system of scoops and neutralizer plates behind the blades [Fig. 2(a)] where it is neutralized and pumped [Fig. 2(b)], thereby reducing the recycling coefficient and particle inventory. TEXTOR is equipped with 24 fixed Langmuir probes[7,9] which are an integral part of the ALT-II system. These probes provide measurements of the plasma density and temperature and ion flux.

A detailed description of the ALT-II system can be found in the literature,[6,10] therefore we will cursorily describe the probes and concentrate on the probe circuitry. The Langmuir probes, shown schematically in Fig. 3, are located inside the limiter scoops, where the SOL plasma flows towards the neutralizer plates, as shown in Fig. 2(a). The probes are made out of milled high temperature molybdenum TZM alloy (trace amounts of titanium, zirconium as alloying elements) rod, with a melting temperature of 2550 °C, inserted in a TZM sleeve, which is grounded to the blade body as shown in Fig. 3. An alumina tube separates the probe from the sleeve, providing electrical insulation. The plasma conditions in the SOL of TEXTOR discharges are such that TZM is a suitable material to withstand the heat fluxes and physical and chemical erosion. The area of the probes varies from 0.5 cm^2 to 0.65 cm^2 depending on their placement in the ALT-II system.

The main motivation of this work is that sudden discharge terminations in tokamaks, called disruptions, create power surges in the Langmuir probe circuitry and produce extensive damage on the resistor networks and power supplies that result in costly down time. The main culprits for the damage are the halo currents induced in the limiter structures and liner and due to the plasma current quench. Immediate and even short and medium-term (days) access to the circuitry can be restricted or impossible due to residual radiation from the presence of neutron-activated materials in and around the tokamak and thus prompt diagnosis and repair of the systems can be impaired. Installation of the equipment outside the radiation bunker involves long cables, ducting, larger capacitive losses and cost and thus is not always an option. Therefore, ease of remote diagnosis and maintenance are paramount to reduce expensive downtime and to reduce personnel exposure to residual radiation. It is also desirable to allow for expandability and ease of modification in the system by building it modularly and with standardized components.

Two approaches can be taken to improve probe system availability. The first is to upgrade the protection systems to reduce or eliminate the damage to the circuitry and the second is to increase the ability to diagnose problems remotely thus easing in-experiment repairs. The circuitry described in this manuscript features a variety of innovations. The use of DIN-rail modules in the circuit construction assures flexibility, scalability, ease of maintenance and modularity in a cost-efficient manner. The use of a combination of metal oxide varistors (MOVs) and fuses assures flexibility in surge handling and ease of repair and maintenance. The introduction of a test circuit addresses the issues of remote diagnosis and control. Recommendations for further improvements are given.

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FIG. 1. The inside of the TEXTOR-94 vacuum vessel showing two of the ALT-II blades and the three poloidal limiters.

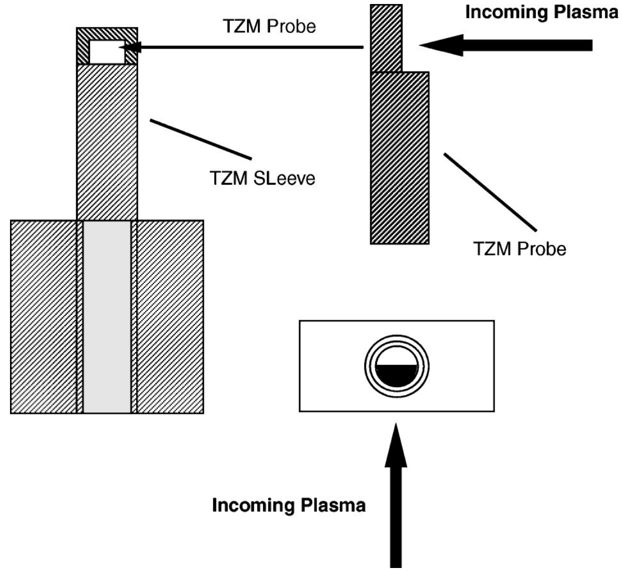

FIG. 3. Schematic of a typical ALT-II probe showing the tungsten sleeve and probe and the alumina insulation.

II. PROBE SYSTEM AND CIRCUITRY DESCRIPTION

The circuitry for the probe system provides power to the probes and allows measurement of the applied voltage and resulting current using a CAMAC-based data acquisition system. The probe current is given by[12]

$$I_{\rm pr}=I^{+}-I^{-}\exp\{e(V_{\rm pr}-V_s)/kT_e\}$$
$$=-I^{+}[1-\exp\{e(V_{\rm pr}-V_{\rm fl})/kT_e\}, \quad (1)$$

where $I^{+}=0.5en_eSc_s$ is the ion saturation current, $I=-0.25en_eSc_e$ is the electron saturation current, $c_s=[k(T_e+T_i)/m_i]^{1/2}$ is the sound speed, $c_e=[8kT/\pi m]^{1/2}$ is the average electron velocity, S is the effective collecting area, V_s is the plasma potential, $V_{\rm pr}$ is the probe potential, $V_{\rm fl}$ is the potential at which the probe current is zero, and m_i is the ion mass.

Some of the probes are used in single probe mode, where the voltage applied to the probe is swept to obtain a probe characteristic given by Eq. (1), and from which the electron temperature and density can be extracted by three-parameter fitting (assuming $T_e=T_i$). The other probes are used in ion saturation mode, where the applied voltage is negative, constant and high enough that only I^{+} is collected. It is roughly proportional to particle flux. Both types of probe operation require the following components, as schematized in Fig. 4:

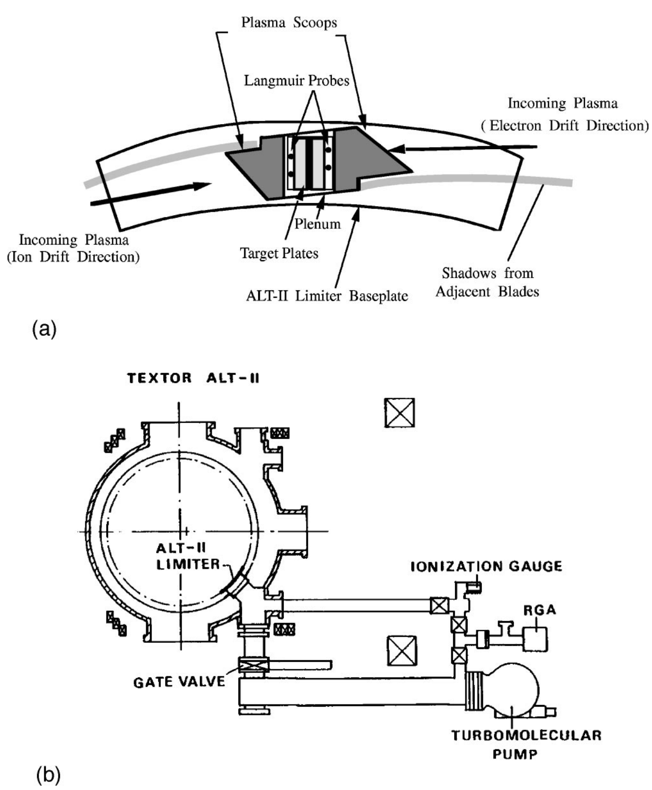

FIG. 2. (a) Back of the ALT-II limiter blade showing the scoops, target plates, plenum and probes. (b) Schematic of the ALT-II system and location in the TEXTOR-94 vacuum vessel. ALT-II consists of eight identical blades that form a toroidal belt.

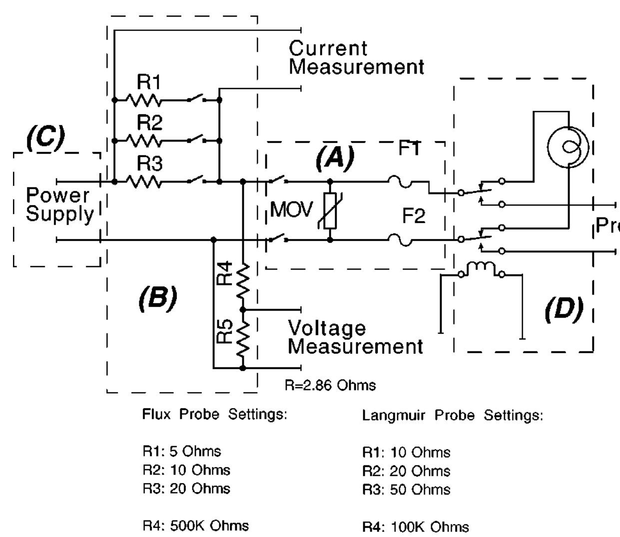

FIG. 4. Schematic of the probe electronics showing the input, current and voltage measurement, B, and the protection and control section, D. The resistor values for the various configurations are noted.

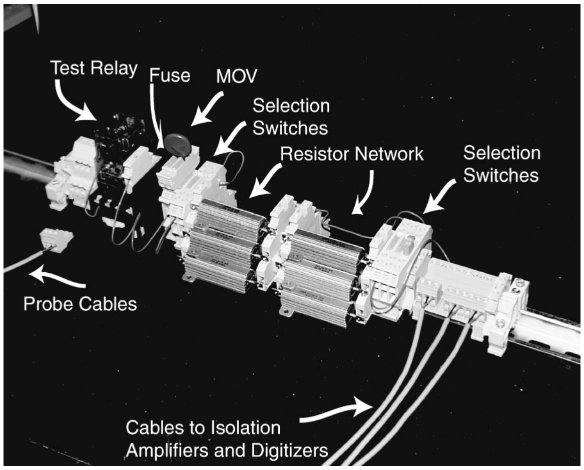

FIG. 5. Photo of a typical modular probe circuit built on DIN modules. All interconnections are not implemented for clarity.

(A) Input/protection section;
(B) measurement section;
(C) power supply section; and
(D) test/control section.

A. Input/protection section

The signals from the probes are transmitted to the circuitry using kapton-insulated coaxial cables inside the vacuum and shielded twisted-pair cables outside the vacuum. The body of the limiter blade is used as ground for each probe; the blades are, in turn, connected to the vacuum vessel, which is grounded via a 10 Ω resistor. The cables are connected to a standard DIN input block as seen in Fig. 5, thus no soldering is needed.

The protection section, seen in Fig. 4, contains two main elements, two slow-blow fuses in series with the probe cables and a metal oxide varistor (MOV) in parallel, assuring that any voltage transients will be discharged. Both components are mounted in standard DIN modules, as shown in Fig. 5, allowing fast replacement. The MOVs will start conducting at either 320 or 420 V and can absorb as much as 6000 A in pulse mode (for 20 μs) for a total of up to 100 J. The MOV parameters were chosen based on detailed current detection and infrared imaging of disruptions[11] showing that the ALT-II limited is bombarded by a rapid sequence of heat pulses varying from 10 to 100 μs. The voltage and current transients in the probe circuitry are produced by halo currents due to the plasma current quench during these times. Currents above 5–6 A will interrupt the circuitry by blowing the fuse and we have found that slow-blow fuses work best by preventing premature protection. This section assures that the MOV's will dissipate most energy surges and that only high current pulses will require replacement of the fuses, which being mounted in DIN-rail receptacles, can be easily replaced.

B. Measurement section

The measurement section, seen in Fig. 4, comprises a network of 25 W wire-wound resistors, shown in Fig. 5, connected to a unity-gain isolation amplifier bank and a CAMAC-based data acquisition system. Part of the network acts as a voltage divider and provides a signed proportional to the applied voltage and the other part of the network acts as a shunt resistor that provides a signal proportional to the probe current. The voltage signal must be taken at the probe side of the shunt rather than at the power supply side to account for voltage drops due to the circulating current. The use of standard DIN-module switches, shown in Fig. 5, allows selection of multiple resistor configurations to accommodate various plasma conditions. The resistors are mounted on DIN modules that permit fast replacement in case of damage and convenient modifications. The output signals from the network, which can have a high voltage component, are fed to isolation amplifiers based on the Burr Brown 3652 optical isolation amplifier. The amplifiers are designed for differential input and work at a fixed gain of 1 with a bandwidth of 10 kHz.

C. Power supply section

The power supply section consists of either dc custom-made supplies or programmable bipolar power supplies from Kepco, all of which are isolated to 3 kV by isolating transformers. The dc supplies are set at −100 to −325 V dc to assure full saturation and can provide up to 5 A before a protection fuse is blown. The Kepco power supplies (BOP100-4M) can act as 100 V, 4 A, power amplifiers up to 10 KHz. In this case, the Kepcos, controlled by a programmable function generator, provide a ramp for 12 ms from −60 to 20 V (dc offset added to assure ion saturation) every 100 ms during the discharge. The current and voltage data follow the single probe characteristic of Eq. (1) and are processed with a multivariable nonlinear fitting routine to obtain the temperature and density of the plasma in the scoop.

D. Test/control section

The test/control section is comprised of locally operated relays and lamps/light-emitting-diodes (LEDs), configured as shown in Fig. 4, so that the circuit and power can be connected to either the probes or to visible continuity indicators. The operator is thus able to quickly test all the power supplies, fuses, MOVs and resistor network at a glance and proceed to replace the fuses if the lamps/LEDs are not lit. The system also enables the disconnection of the circuitry from the individual probes in case of irreparable damage inside the vacuum vessel.

III. DATA AND DISCUSSION

The discharge evolution during a high power, 4 s long, TEXTOR discharge is displayed in Fig. 6. The plasma density and current are plotted in Figs. 6(a) and 6(b). The current from saturated or swept probes located in the ion or electron drift side of ALT-II are shown in Figs. 6(c)–6(f). Note that the electron side current is lower than that in the ion side current, a previously reported poloidal asymmetry[3,13] in the discharge. The traces in Figs. 6(c) and 6(d) show the current from two probes operated at a constant voltage, i.e., in the flux mode, whereas Figs. 6(e) and 6(f) show the current from swept probes. Note the increase in current reflecting the rise in density and input power (not shown). The swept currents

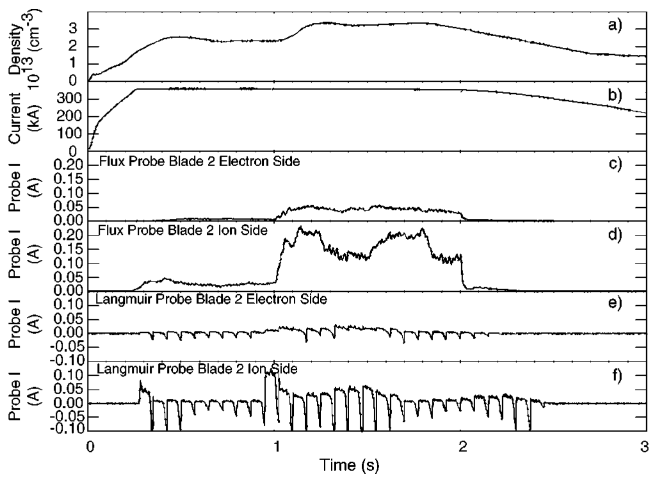

FIG. 6. Typical TEXTOR-94 discharge evolution showing (a) plasma density, (b) plasma current, (c) flux probe current, electron side, (d) flux probe current, ion side, (e) Langmuir probe current, electron side, (f) Langmuir probe current, ion side.

show negative incursions towards the electron saturation branch and the positive, flat excursions into ion saturation current [I^+ in Eq. (1)].

Although the failure rate of equipment depends markedly on operating conditions, we found that complex and costly repairs, usually involving the Kepco power supplies, were reduced to zero after the implementation of this circuit. The failure rate of power supplies decreased from eight failures/year to zero failures/year and that of the resistor network to zero failures/year. Only fuses had to be replaced at an average rate of ten fuses/month. We therefore consider the new circuit design a considerable improvement over previous designs.[7,10,13]

It was also found that failures (usually blown fuses) could be located and repaired within 2 min during operation. Since the shot repeat rate is nearly 6 min, the equipment could be kept operational without disturbing operations not exposing personnel to radiation above permissible limits.

Finally, additions and improvements to the system were performed on various occasions by just adding extra DIN modules or easily replacing existing components by others with different specifications. Maintenance time was thus reduced dramatically from four man-months/year to less than one man-month year.

IV. FURTHER IMPROVEMENTS AND OTHER SOLUTIONS

The system reported here, chosen for its simplicity and low cost, can be improved further in order to increase reliability by:

(1) Decoupling the current measuring elements from the probes by eliminating the shunt resistors and replacing them with Pearson transformers for the ac current measurements and Hall-based sensors for the dc current measurements; and
(2) exposure of personnel to the radioactive environment can be reduced by implementing a relay-based remote fuse selection system and the more costly option of placement of the fuses and MOVs outside the radioactive area.
(3) Alternative schemes considered included an automatic system that detects overcurrent and shuts down the circuit temporarily. Tests of such a system yielded the result that it was very difficult to find an operating window for the protection threshold that would prevent damage to the power supply and measuring circuitry while reducing false alarms to a permissible level for a wide range of operating regimes. These difficulties are probably particular to TEXTOR's limiter configuration and operating modes, and it was deemed simpler and less costly to proceed with the system described here.

ACKNOWLEDGMENTS

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