ITER Langmuir probes: Physics and technological issues under investigation in the WEST tokamak

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Abstract

This paper describes some of the physics and technical issues facing Langmuir probe design for ITER, and which are being investigated in the WEST tokamak.

1 Physics issues : flush-mounted probes

The ITER divertor consists of actively cooled tungsten monoblocks (MB) bonded to CuCrZr cooling tubes, and will be subjected to heat flux near the limits that the technology can tolerate [1]. Great care has been taken to avoid exposing MB leading edges to intense heat flux impinging on the divertor at glancing angles of incidence [2]. The Langmuir probes (LP) in ITER [3] will be attached to the sides of the divertor targets to measure the plasma parameters at the divertor plasma facing units (PFU). The LPs themselves consist of a tungsten cylinder covered with a thin layer of alumina for electrical insulation, which is inserted into a tungsten heat shield. The heat shield protects the probe body from photon radiation and is brazed to the tungsten divertor target, which is water-cooled and conducts the heat away from the probe. The system is in the final design stages, and will be ready for initial pre-fusion plasma operation.

The WEST tokamak [4], until 2021, was equipped with an uncooled lower divertor made of W-coated graphite targets, and an actively cooled upper divertor made of W-coated CuCrZr targets. Because LPs must be electrically insulated from the divertor while having good thermal contact with it, LPs will suffer harsher operation conditions than the divertor itself, so they must be flush-mounted to avoid melting them [5]. Flush-mounted LP (FMP) arrays, provided by IPP Prague [6], were installed at two toroidal locations on the lower divertor. Good alignment is essential to providing reliable measurements [5], and is an issue that must be addressed in the ITER LP design. Care was taken to ensure that the WEST probe tips were aligned as well as possible with the surface of the divertor target, within ±20 µm. Sweeping the divertor strike point across several probes demonstrated that each probe is identical in terms of charge collection. Details about the design can be found in [6].

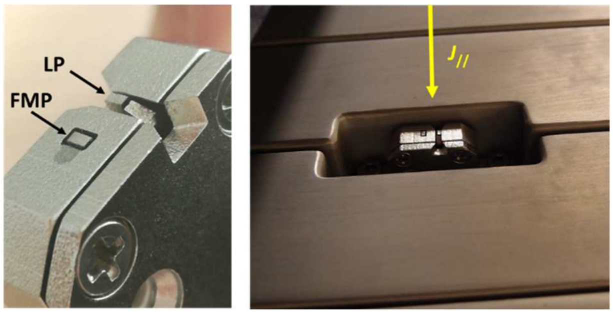

Figure 1. Left: probe head equipped with a FMP and a classical "proud" LP. They are 4 mm apart poloidally. Right: view of the probe head retracted 4 mm below the surface of the lower divertor.

Even if good alignment is ensured, analysis of FMP data is complicated. Usually LPs are designed to have cross-field dimensions larger than the ion Larmor radius and the Debye sheath thickness, so that the ion current collected for negative bias voltage saturates. In the case of FMPs, the probe surface projected along magnetic field lines can be smaller than that, and the ion current, dominated by sheath expansion, does not saturate with voltage [5]. In collaboration with the Southwest Institute of Physics (Chengdu, China) and ITER, a dedicated system was installed in WEST. A magnetically driven coil mechanism (called the "mousetrap") was fitted between the graphite targets and the stainless steel support plate. When a current is driven through the coil it rotates, pushing a probe head from 4 mm below the target to 1 mm above it. It is equipped with a FMP, and a classical "proud" LP having a 1 mm x 1 mm cross

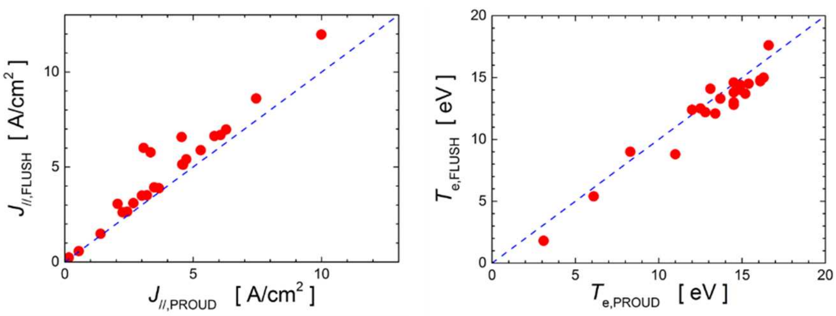

Figure 2. Parallel ion current density (left) and electron temperature (right) measured simultaneously by the FMP and the classical "proud" probe on the lower divertor in WEST. All measurements from the experimental session of December 14, 2018 are shown.

sectional area (Figure 1). Comparison of the two types of probes shows that they both measure the same parallel ion current density and the same electron temperature, despite having very different geometries (Figure 2).

2 Technology issues : cooling and electrical insulation in steady state

The FMPs and the mousetrap system on the lower divertor were built using standard techniques. The divertor was uncooled, and subject to a temperature limit of 1200°C to avoid delamination of the W coating [7], imposing a limit of energy that could be injected into the plasma, so overheating of the FMPs was not an issue of concern. The mousetrap system exposed the probe only once or twice during each discharge, for durations not exceeding 100 ms. Both the divertor and the probes were allowed to cool by radiating for at least 15 minutes between discharges.

The upper divertor, on the other hand, is water-cooled and the LPs installed there had to be designed to work in steady state. Four constraints influenced the design. (1) Poloidal gaps between individual PFUs are all 0.5 mm wide. There are no wide gaps like the 20 mm wide ones that separate divertor cassettes in ITER, and inside which the LPs will be installed. An ITER-type probe geometry therefore could not be envisaged in WEST. (2) The LPs need to be electrically insulated from the divertor, yet at the same time have good thermal contact with it. (3) Each probe body below the small flush-mounted tip has to have a large surface in contact with the divertor to optimize heat flow across the electrical insulator. (4) The LPs have to be made of W to be compatible with the aim of operating with a full W wall in WEST. The three latter constraints concern steady state operation of the ITER LPs, as well.

Figure 3. Above is a side view of wafer probes on an actively cooled upper divertor PFU. Below is a view of the probes on the upper divertor. The heat flow at inner and outer strike points (ISP/OSP) is indicated.

Tungsten "wafer" probes produced by powder injection moulding were provided by Karlsruhe Institute of Technology [8]. The probes are flat slabs 2.7 mm thick featuring a small plasma-exposed tip and a flared geometry to spread the heat and provide enough surface contact with the divertor to evacuate it. Cavities were machined from the sides of the PFUs to house the probes. Two flat-headed screws press the wafers onto the PFU. They are insulated from the probe by alumina tubes through which the screws are inserted, and phlogopite mica rings under the screw heads. Between the PFU and the probe two types of electrical insulation are being tested: (1) 0.1 mm thick phlogopite mica sheets and (2) 0.1 mm thick layers of high velocity oxygen fuel (HVOF) sprayed tungsten. Alignment of the probe tips with the surface of the PFUs is provided by a tightly toleranced (±5 µm) alumina pin.

Thermomechanical simulations predict a tip temperature of ~800°C for 12 MW/m^2 perpendicular to its surface. The temperature under the screw heads, where greatest thermal contact is expected to be, will not exceed 500°C which is well below the allowable peak operating temperatures of both phlogopite mica (1000°C) and alumina (~1800°C). Until now 59/60 of the probes that were installed are still working, with no sign of degradation. They have survived discharges up to 1 minute long, and have been exposed to a total of 55 minutes of plasma since the beginning of WEST operation.

Summary. A number of studies dedicated to addressing design issues of the ITER Langmuir probes are underway in WEST. The LPs in ITER, and in any high power, steady state device, have to be flush-mounted to survive. We have shown in WEST that alignment of the probes is very important. Comparison with a reciprocating classical "proud" probe at the same point on the divertor demonstrates that flush-mounted probes data can be analyzed with confidence. Wafer probes on the actively cooled upper divertor achieve the goal of good thermal contact to provide adequate cooling, and at the same time, electrical insulation.

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