Development of a pop-up Langmuir probe array for the W7-X high-heat-flux divertor

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1. Introduction. In Operational Phase 2 (OP 2) of the Wendelstein 7-X experiment, Langmuir probes are foreseen in two modules of the water-cooled high-heat-flux (HHF) divertor [1]. Since the probes will not be water-cooled, they must be periodically retracted from the plasma in order to survive through the long-pulse (30-minute) discharges. In this paper, we present an overview of the current state of development of a pop-up probe set designed to meet the stringent physics and engineering requirements of W7-X.

2. Main requirements. To meet the physics objectives of W7-X, the projected area of the magnetic field onto the probes must be known to within 10% so that the edge density may be diagnosed with sufficient precision. In addition, the probe tips must not reach temperatures at which thermionic emission would obfuscate the probe signal (e.g., 1800°C for graphite [2]). Furthermore, the system of cables connecting the probes to external measurement electronics must accommodate fast measurements using the “Mirror Langmuir Probe” system as described in [3].

The probes must also meet challenging engineering requirements for successful integration with the HHF divertor. For one, each probe, as well as its insulation from the target module, must fit inside a cutout on the edge of the target with a diameter of 4 mm. All in-vessel instrumentation must be able to withstand 50 kW/m^2 of stray ECRH radiation [4] – or be adequately shielded. The drive instrumentation must be durable enough to last for the approximately 100,000 plunge cycles anticipated over the course of OP 2. Finally, since the probe tips are expected to have a shorter lifetime due to their direct contact with the plasma, it must be possible to remove and replace the tips from the plasma side of the divertor (i.e., without needing to remove the divertor) during maintenance periods when the vessel is vented.

3. Overview of the present design. A CAD model of a basic unit of two probes and one driving mechanism is shown in Figure 1a. The drive unit (i) consists of a rigid coil that rotates in response to the Lorentz force in the W7-X magnetic field. The coil will be realized by printing gold tracks on a multi-layered ceramic circuit board. The housing (ii) shields the instrumentation from ECRH stray radiation. Fixations (iii) form a rigid connection between the replaceable probes and the permanently-installed drive unit and electrical contacts. Flexible contact strips (iv) form connections between the moving probes (via their fixations) and stationary external biasing cables. A traverse (v) connects the drive unit mechanically to two probes, and imparts flexibility to guarantee full insertion of both probes even in cases of small height differences. Ceramic stoppers (vi) fix the depth of insertion into the plasma. Ceramic guide tubes (vii) guide longitudinal motion and maintain electrical isolation from the target module. Each guide tube is also encased in a steel shell (not shown in the figure). Ceramic grooves (viii) prevent the fixations and probes from rotating. The probes (ix; see also Figure 1b) have graphite tips brazed to molybdenum bodies. The tip has a triangular shape, and its exposed surface will meet the magnetic field at an angle of 15° or 30° depending on the variant used. The diameter of the tip does not exceed 3 mm.

Figure 1c shows a view of a set of 12 probes on the edge of a target module. The probes are spaced 25.4 mm apart. Since the adjacent module will have additional probes spaced at the same interval and staggered with some of the probes shown in the model, the effective poloidal spacing will be as low as 12.7 mm. Also shown in Figure 1c is the pipe system which leads the electrical cables from the drive units and probes to the external electronics via a feed-through.

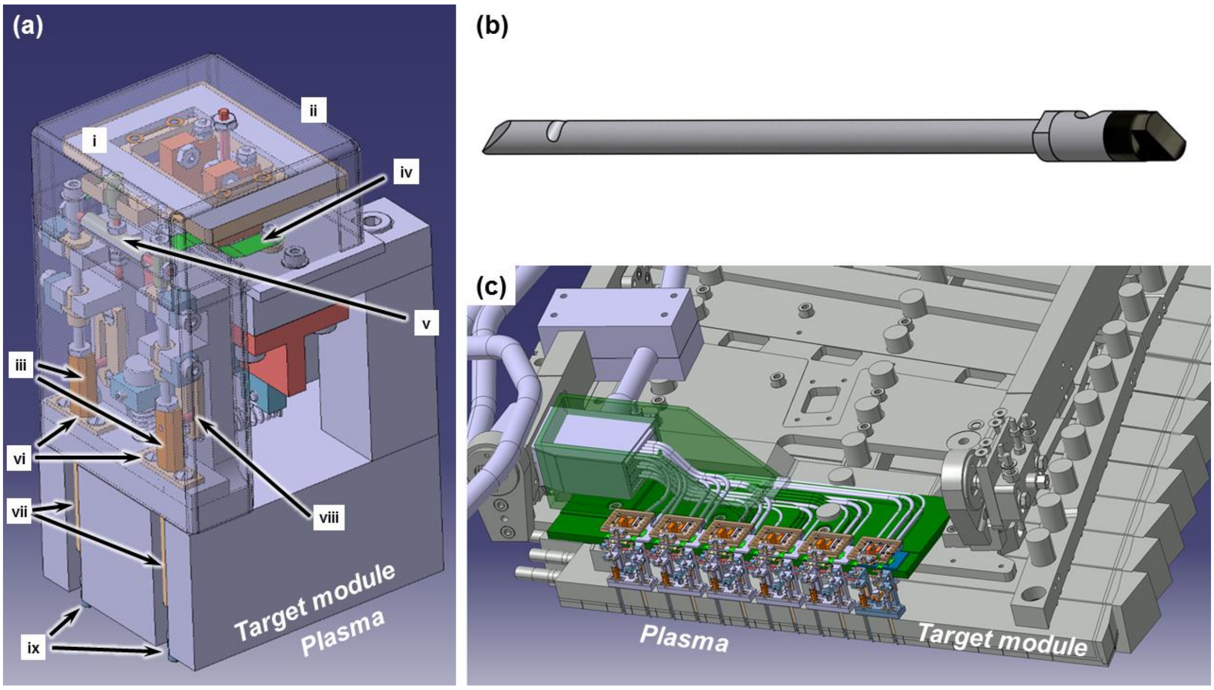

Figure 1. (a) CAD model of two probes and one drive unit with labels indicating the different components described in the text. (b) Replaceable probe. (c) View of 12 probes and 6 drive units on a target module, as well as the cable conduit system.

4. Technical challenges. One significant challenge in the design of this diagnostic was to develop a cabling system that was feasible to mount during the target module installation. In particular, cables from instrumentation mounted on the targets must be routed through pipes fixed to the vessel wall; however, once the target module is put in place, there is no room for a person to reach behind the module to make the connection by hand. Hence, a system was developed wherein the connection would be made automatically with the placement of the target module. Cables originating from the probes and drive units on a target module are collected into a target-mounted connector box (Figure 1c). Before the target module is installed in its final position (and there is still room to reach behind where the target will eventually sit), a person will thread the cables into the wall-mounted pipe (Figure 2a). The cables will be held taut from the opposite end of the wall pipe as the target is brought into place. Finally, as the target module is moved into its final position, the conical outlet of the connector box will slide into the opening of the pipe and form an ECRH-proof connection (Figure 2c-d).

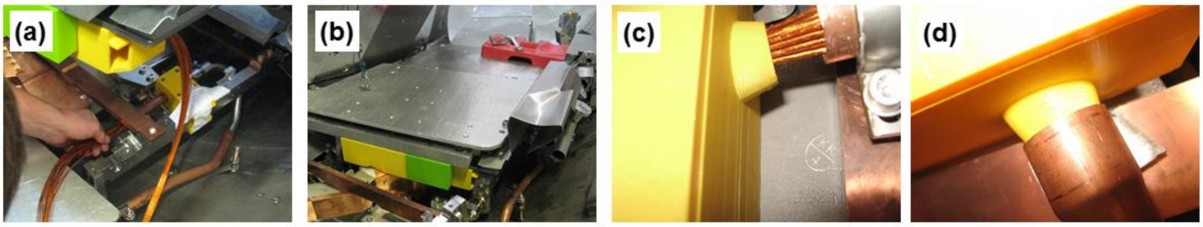

Figure 2: Photographs from a test of the installation procedure for an instrumented target module. (a) Cables from a prototype connector box (yellow) are threaded into a wall-mounted conduit. (b) Target module is lowered into a preliminary holding position. (c) View of the box, cables, and pipe when the target is in the holding position. (d) Components after the target is pushed into its final position.

Another challenging aspect of the design was the realization of a probe tip that could be replaced from the plasma side of the divertor without the need to touch any instrumentation behind the target. This was implemented through the fixation shown conceptually in Figure 3a-d. One side of the fixation contains an elastic strip of metal which pushes a bolt in through a hole on the wall. When a probe is inserted, the screw is pushed out until it snaps into place on a groove in the probe body. During removal, the probe is first rotated in order to retract the bolt and then pulled out of the fixation. This operation is enabled with a custom-built tool consisting of a thin-walled cylinder with an internal protrusion on one end (Figure 3e). This protrusion is guided into a groove near the probe tip (Figure 3f), which allows for pulling, pulling, and rotation. Note that the probe need only be rotated in one direction for the removal procedure.

5. Tests and simulations. A number of additional aspects of the design have been informed by tests or calculations. Finite-element modeling conducted in [5] has led us to restrict the duration of each plunge cycle to 100 ms or less with a duty cycle of 1% in order to avoid overheating of the graphite tip. Measurement of the Lorentz force delivered by a drive unit with a single-turn coil in [5] indicate that one can expect roughly 0.1 N of driving force per Ampturn of coil current. Since static frictional forces may exceed 0.5 N, this has led us to pursue a multi-turn coil to reduce the required current per turn.

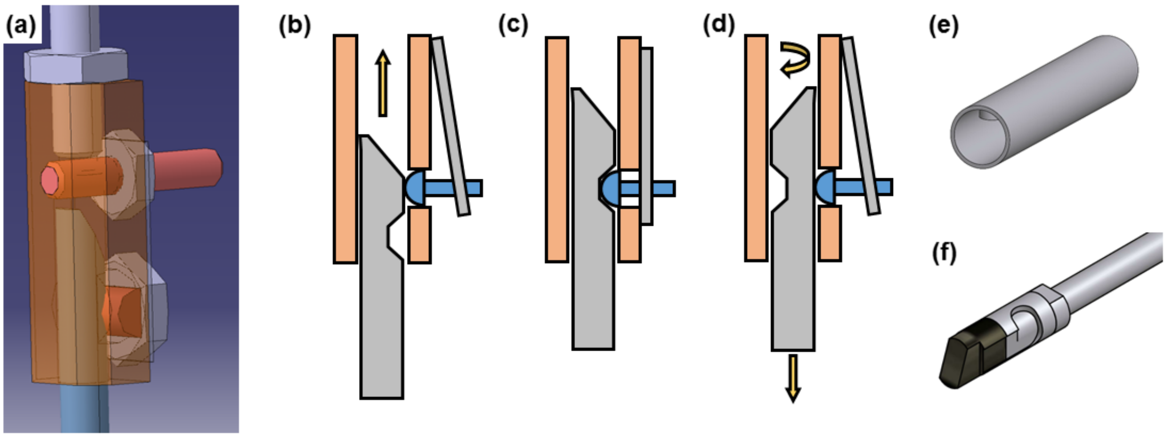

Figure 3: (a) Detail from the CAD model of the probe and fixation. (b) Conceptual illustration of the insertion of the probe into the fixation. (c) The inserted position, after the probe has snapped into place. (d) Removal of the probe. (e) Removal tool. (f) Detail of probe tip showing interface to removal tool.

In addition, to enable fast measurements, the in-vessel cables to each probe were originally specified to be coaxial and rated for 50 Ω. However, the stiffness of vacuum-compatible coaxial cables would have made installation difficult. Fortunately, it was found that a more pliant cable consisting of a shielded twisted pair exhibited nearly identical behavior to a 50 Ω coaxial cable in response to transient signals if one of the inner wires was short-circuited to the outer shield. Hence, we have adopted this cable to carry the probe signals.

6. Next steps. Prototypes of the instrumentation shown in Figure 1a will be tested for performance and longevity in the D-MAG superconducting magnet located at the University of Greifswald. Construction and installation of the finalized components is planned for 2019 and 2020, and operation will begin with W7-X Operational Phase 2 in December 2020.

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