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Diagnostic Setup for the Divertor Manipulator at Wendelstein 7-X

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Abstract

The investigation of plasma wall interactions in terms of erosion processes, fuel retention and new plasma facing components exhibits a scientific gap as discharges in tokamaks and stellarators last only seconds up to a minute. Currently, linear plasma machines are bridging this gap, while Wendelstein 7-X (W7-X) will provide steady-state discharges of up to 30 minutes in its second operation phase (OP2), in which a divertor manipulator is envisaged to expose samples to reactor-relevant plasma fluxes and fluences. With a design following the limiter lock system at TEXTOR and the DIM-II at AUG, the divertor manipulator at W7-X aims to study plasma surface interactions ex-situ by daily/weekly probe exchange and in-situ by embedded diagnostics and an observation system.

The design, layout and capabilities of the embedded and observing diagnostics determine the accessible parameters for the in-situ investigation of the exposed probe materials, ranging from plasma edge measurements in the manipulator shaft to intersecting the magnetic island structure on the manipulator head. A versatile laser and observation system adds active surface analysis techniques. To prevent local overheating and excess thermal stress, essential diagnostics for temperature control are identified and combined with first considerations of the manipulator head shaping, based on the field line tracing tool of the W7-X web-service.

Keywords: Fusion, Wendelstein 7-X, Plasma Diagnostic, Divertor Manipulator, Plasma Surface Interaction

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1. Introduction

The investigation of plasma material interactions in the nuclear fusion context forwards to reactor-grade materials for the first wall and the divertor. While the first wall is primarily affected by radiation and only moderate heat loads, the divertor of a fusion reactor is additionally subject to the highest plasma fluxes in the reactor. In order to qualify next-step plasma facing materials and components for this high-heat-flux divertor region, a divertor manipulator system (DIMS) is being developed for Wendelstein 7-X (W7-X) for its second operation phase (OP2), scheduled for mid-2020. The main purpose of the DIMS probe manipulator is carrying multiple samples and diagnostics with the capability of handling the typical divertor heat load of $10\,\mathrm{MW/m^2}$. By allowing up to 30 min of plasma operation, the stellarator Wendelstein 7-X is ideally suited for a plasma–material interaction (PMI) program and bridging the gap between pulsed tokamaks and linear plasma generators.

Plasma conditions comparable to the steady-state conditions in the ITER or DEMO divertor for material qualification are achieved in linear plasma generators [1, 2, 3] by discharges over a whole working day and sample biasing to imitate higher ion energies. Exposing surfaces via removable divertor/limiter elements in the tokamaks TEXTOR and AUG [4, 5]) has proven to be quite successfully, especially through extensive diagnostic coverage of the surface and the adjacent plasma region around. Therefore, these designs are considered carefully for the DIMS at W7-X in the current design and following prototype stage. Furthermore, short time material exposures in W7-X are made available by the multi-purpose manipulator (MPM) [6, 7], which is usually equipped with various smaller measurement units, but serves as important design input for the drive system, exchange chamber and safety consideration.

The exposure of retractable/exchangeable material and component samples to divertor plasma conditions has been realized in different ways. Exchanging part of divertor itself with a removable tile was done in AUG and provides the closest resemblance of divertor conditions. A considerable drawback is that with a failure of the tile or the manipulator, the plasma operation would be prohibited, which was a major concern for this design in W7-X. The limiter lock system at TEXTOR used a test limiter design with embedded diagnostics and variable insertion depth, allowing different loading conditions and the study of the SOL plasma. For the DIMS, selecting a suitable position within W7-X and its interaction with the magnetic topology was already described in [8], wherein the low-ι end of the horizontal target was identified as ideal location for a controlled high heat flux exposure. In this way the DIMS is rather flexible and can act as a limiter, intersect islands and/or its separatrix or stay just in the shadow of the divertor for measurements or low flux exposure. The first operation of the DIMS is foreseen for OP2, in which a probe head without water cooling, i.e. a inertially cooled probe head, is used first to accelerate the design and testing. Furthermore, this procedure allows design and operational (safety) feedback for the steady-state water cooled probe head.

This article focuses on the proposed diagnostic equipment of the DIMS embedded in the probe head(s) and the external laser and observation system. The embedded diagnostics will deliver information about the plasma environment to aid in-situ analysis but also general divertor/SOL plasma characterization. The laser and observation system adds visual/IR imaging, passive and active spectroscopy. Furthermore suitable diagnostic capabilities for the DIMS in order to fulfill the PWI study aspects are evaluated, including the observation and laser injection system. Due to the larger size of the probe head, appropriate numbers, positions and design adopted to steady-state operation are identified. In the last section the W7-X web-service tools are used for basic probe head/surface considerations.

2. Diagnostic Setup

The DIMS will be situated at port AEM20 and the drive system points almost vertically up towards the plasma center, which can be seen from the labeled components in Figure 1. Thus, the movement of the probe head inside the chamber is predominantly in the (small) radial direction, which is beneficial in terms of heat load stability. The laser and observation system is situated in the same poloidal cross-section in port AEO20, shown in the upper right corner of Figure 1. The support structure of the probe head is large enough to carry water cooling pipes, a gas feed and $\geq$60 standard BNC cables, allowing a large number of power connections and signal cables. The exchange chamber below the cryostat is easily accessible and allows changing the probe heads within a few hours, which is essential for ex-situ analysis without "contamination" by other gases or experimental conditions.

The internal and external diagnostics setup serve two main purposes. Established and reliable techniques like Langmuir probes, thermocouples, IR observation and a gas injection system measure local plasma and probe parameters, used for the interpretation of e.g. erosion rates, retention or surface morphology changes. Additionally, the edge and SOL plasma can be characterized with spatiotemporal resolution by embedding arrays of probes, visual imaging and spectroscopy. Another utilization of the DIMS is testing new reactor-suitable diagnostics, especially in view of a steady-state operation under high heat loads.

2.1. Probe Head

The probe head combines the exposed surface areas like samples and diagnostics on the surface and inside. While in a later stage probe heads are tailored to magnetic configurations, the first inertially cooled probe head focuses on a larger number of diagnostic implementations suitable for all configurations, yet still leaving surface area for material exposure. The material of choice for all plasma wetted areas and components of the probe head is tungsten, tungsten composites and other high-Z materials, especially in view of reactor relevance.

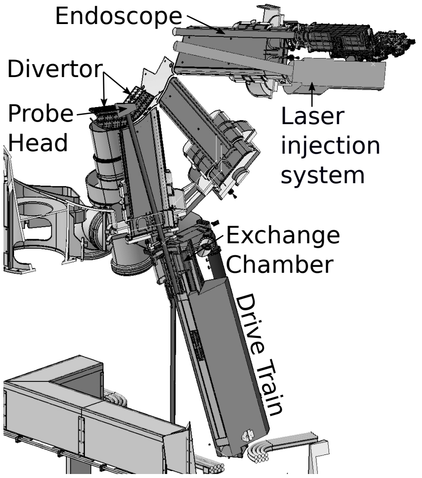

Figure 1: CAD drawing of the manipulator system (blue), the endoscope system with approximated optical path (orange) and the laser injection system (green).

However, for the diagnostic-heavy inertially cooled probe head, carbon is possible and would avoid accidental release of tungsten into the machine.

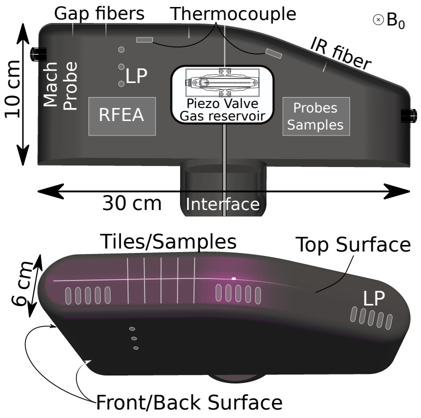

Figure 2: Probe head with diagnostic probe positions.

Langmuir probes are widely used for measuring the local plasma density, temperature and potential with 1 mm spatial resolution and will also deliver plasma flux estimates for the PWI aspect of DIMS. Time resolutions down to 1 μs in a single point are usually only achievable for one plasma quantity. However, sophisticated electronics in the mirror Langmuir probe (MLP) design [9] can overcome this restriction adding SOL turbulence study capabilities and their influence on PWI. Requirements for a sufficient signal transmission are coaxial cables, antenna/dummy wires in the probe head and short cables ($< 10\,\mathrm{m}$).

Due to the massive heat loads a flush mounted probe design is mandatory for the top surface probes and the heat transport from probe tip to bulk or cooling structure must be ensured. The necessary electrical insulation between bulk and probe tip can be realized by a vacuum gap, which is thermally insulating or an insulating material, which could be deposited/sputtered with conducting impurity and lead to arcing. Since mechanical support between bulk and probe tip is needed anyway, a common compromise is leaving a vacuum gap in the first few mm and surround the lower half of the probe tip with a high thermal conductivity material, e.g. c-BN or SiC ($\leq$ 130W/(mK)), which is similar to tungsten or graphite. However, only a good heat transfer through the insulator will prevent the probe tip from overheating and becoming a source for electron emission or deposition of a conducting layer on the insulator. A longer probe tip and direct contact to the insulator proved to be helpful to increase the effective heat capacity.

Five tips are spaced 1 cm to allow poloidally resolved measurements and three of these units are placed in the middle and on either side of the top surface. On the front and back side (protruding) probe tips are spaced to measure radial plasma profiles.

Mach probes as a variant of Langmuir probes measure the plasma flow by comparing plasma flux to a subdivided probe surface. The only location to measure the plasma flow mostly undisturbed by the large volume of the probe head are the rounded side edges of the probe head, as the magnetic field is directed perpendicular to the front/back surface.

Thermocouples are commonly employed for temperature measurements below high heat load areas and used for monitoring and safety feedback. High temperature tungsten/rhenium thermocouples operating up to 2200 °C (Type C,D,G) cover predicted hot spots, while for the actively cooled design a lower temperature range thermocouple with higher precision (Platinum / Rhodium Type B,R,S: $\leq 1500 - 1800\,^\circ\mathrm{C}$ and standard Type K :$\leq 1400\,^\circ\mathrm{C}$) is sufficient since overloading in combination with water cooled components must be avoided.

The application of **Fiber optics** has been tested under neutron irradiation at JET and TFTR, and is considered an important tool for diagnostic access in ITER and future reactors due to the relatively high resilience against radiation damage. Although in a future DD operation of W7-X the neutron flux will stay about two order of magnitude below the levels of JET/TFTR DT operation ($\leq 10^{16}\,\mathrm{s}^{-1}$ [10] vs $\leq 6 \times 10^{18}\,\mathrm{s}^{-1}$ [11, 12]), neutron induced emissions could be visible. In JET/TFTR experiments and tests later, a 300°C operating temperature cured neutron damages, hence quartz glass fibers with polyimid jacket ($\leq$ 350°C) can be tested for their applicability.

A direct observation of the edge/SOL plasma is realized by wide-band optical fibers placed underneath the top tiles of the probe head, collecting light via a (focusing) mirror from in between the tile gaps. The narrow gap protects the mirror, while the gap and mirror shield the fiber from all energetic radiation beyond UV. As the schematic in Figure 3 shows, the collection volume of the fibers will be localized to the edge/SOL region already by geometric means (focal point, intensity $\sim r^{-2}$), and additionally by the localization of the emitted radiation, since each radiative process (recombination, (H,He) line radiation, etc) has (or should have) its emission maximum in the SOL/edge region. Moving the probe head can additionally change the most efficient collection zone and thus radially resolve the emissions. However, the most interesting application/feature of this arrangement is the observation of plasma detachment from below, if the recombination zone extends to or forms at the probe head surface.

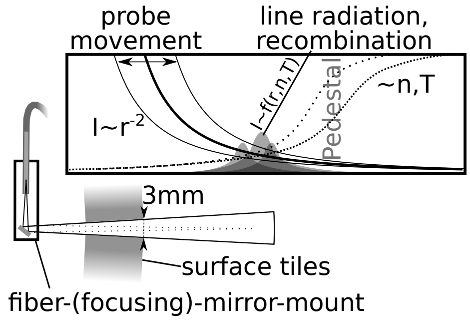

Figure 3: Schematic of optical fiber collecting light through sample tile gap and the localization of light sources.

Another application to be implemented for fibers with IR transmission ($\leq$ 2400 nm) is pyrometry of plasma facing components. Drilling a small hole to collect blackbody radiation from 1–2 mm below the tile surface provides especially at temperatures above 500 °C enough photon signal to measure the temperature without the interference of plasma, scattered microwaves, bremsstrahlung etc. Furthermore, in comparison to slow thermocouple measurements the response time is basically zero and without other light contributions, the temperature correlates directly with the total intensity. The accuracy and high temporal resolution allows the implementation of a fast feedback system for temperature control, but also emergency retract in case of massive overloading, both of which are DIMS-dedicated and independent of the overview IR thermography and the observation system.

A notoriously hard to measure quantity is the ion temperature in the edge of fusion devices, but it strongly influences many PMI processes and is an important input for modeling. Hence at least one measurement method should be included in the probe head design. Ion sensitive probe designs based on the larger gyro radius of ions vs. electrons could only be placed on the side surfaces of the probe head, while the front and back sides are ideally suited to collect ions with a retarding field energy analyzer system (RFEA).

The **Gas injection system** equipped with a piezo-actuated valve allows a wide number of applications, depending on the filling gas and injection velocity. The integration into the probe head reduces the nozzle length to the plasma and the reduced dead volume enables short (1 ms) injections into the plasma. At high pressures (up to 60 bar) the particle numbers are sufficient for gas puff imaging. Lower numbers of impurity gases can be used for migration studies. Particle beams (e.g. He) would require an opening between gas volume and plasma with a scraper/orifice, which could be realized by a special tile above the gas box. However, the benefit of a radially variable particle beams is huge, especially if the source is calibrated and observed from two sides, below by the gap fibers and from top by the observation system described in the following.

2.2. Observation and Laser System

The DIMS surface is just captured in the field-of-view corner of the divertor IR thermography, providing basic surface temperature information. However, the experience with the limiter lock system at TEXTOR showed that a detailed observation of the exposed surface and laser-aided techniques contribute substantially to the analysis of PWI processes. The design of the endoscopes [13] observing the divertor serves as starting point, but can be simplified since the observed area of the DIMS is only 6 cm x 30 cm and the imaging distance varies from 1 m to 1.25 m. Hence, with a scanning 6 cm x 8 cm field-of-view a common 1 Megapixel sensor already reaches a sub-mm resolution and only one axis has to be rotatable.

Dichroic and regular beam splitting mirrors distribute (spectral) parts of the lights to dedicated sensors or spectroscopes. For thermography the IR part of spectrum is separated first, since it is always present, while the second most prominent spectral feature, H_α, also deserves a dedicated band pass filter. The large number of different transition lines of helium, molecular compounds and impurities requires overview spectrometers, but also spectrally narrow fast imaging for transport studies or gas puff imaging using the gas injection system. One compromise is spectral splitting into two or three regions via low-, band- and high-pass filters and subsequent imaging, maximizing the utilized light, while spectrometer inform about the dominant wavelength in each spectral section. For sufficiently high photon emissions imaging one single spectral line per shot/discharge with rotating narrow-band filters has been commonly used.

2.3. Laser

Laser-aided techniques or active spectroscopy and their application in a reactor context are important for fuel retention and surface investigation and modification. Since the port size allows both laser and observation system, the laser system does not require observational capabilities. To reach the minimum spot size at any top surface position, the laser beam exit or focusing element must be manipulated in three dimensions for lateral and axial focal point movement. The latter can also be utilized to spread and lower the power density of the laser. While high powered welding lasers with ms pulse lengths are commonly used with fibers, the power density of ns- and especially ps-lasers is magnitudes larger. However, given a sufficiently thermally stable and cooled fiber with flexible laser systems for injection, a number of in-situ analysis techniques are available, all of which are using spectroscopy.

The lowest power (at moderate to high pulse energy) is required for laser induced desorption (LID), where the laser pulse heats a thin surface layer and removes dissolved or trapped gases. Upon exiting, these gases are excited in the plasma and the fuel retention can be inferred.

Power or energy reserves of the laser system can be utilized to increase the active area, i.e. deliberate defocusing of the spot size.

With increasing laser power densities (higher than the thermal conduction in the material) the surface layers are eroded, enter the plasma and are excited, which is called laser induced ablation spectroscopy (LIAS). Newly formed or prepared layers can be eroded to infer the species or induce transport.

Laser induced breakdown spectroscopy requires besides high energy density a secondary laser pulse to ionize the ablated material, or energy densities which directly create a plasma from the ablated material by e.g. a coulomb explosion.

2.4. Additional features

Similar to the MPM, a number of additional diagnostics or usage scenarios of the DIMS are possible. To cover as many as possible, the layout of the drive system and connection interface will have enough margins in term of cable numbers and power rating. The large front and back surface could be used for dust or impurity collection, or even measuring deposition in-situ by a quartz-micro-balance. Biasing probes to high voltages ($\leq$ 500 V) as a deliberate source of impurities is compatible with the power ratings. Magnetic probes can be easily integrated inside the probe head as well as further fiber arrays with tangential (toroidal) field of view. A potential high power application is inducing strong electric fields, even radially flexible, in the edge/SOL region for global confinement studies [14].

3. Heat Load and Probe Head Shaping

The design goal of the probe head surface shape is an equally loaded surface to reach high plasma fluence over a large number of samples. However, the large range of magnetic configurations, uncertainties of the heat load distribution caused by error fields and bootstrap currents lead to the initial compromise of the diagnostic head being shaped as seen in Figure 2. Shapes dedicated for a particular magnetic configuration are foreseen once the configuration space is sufficiently explored and favorable conditions for long pulse lengths (or otherwise beneficial for PWI) are identified. The heat load estimates are based on a field line tracing technique provided by the W7-X web-service tools [15], where particles following the magnetic field lines represent the fractional power load and diffuse radially by a random walk towards the targets. A description of the implementation can be found in [8], where the integral heat flux to different probe head locations at different insertion depths was calculated. The assumed plasma parameters in the SOL defining the random walk probability are similarly: electron temperature $T_e = 35\,\mathrm{eV}$, average density $n = 1.5 \times 10^{19}\,\mathrm{m}^{-3}$ and a cross-field diffusion $\chi_\perp = 3\,\mathrm{m}^2\mathrm{s}^{-1}$. Using enough particles ($\sim 10^6$) starting from points uniformly distributed over the last closed flux surface, heat load patterns are comprehensive enough to serve as input for shaping the probe head surface.

The first shaping aspect is determining the inclination of the probe head surface, which would theoretically follow an exponential function similar to the limiter [16]. For the DIMS, the heat load comes mainly from the backwards direction, hence an inclination of 5° towards the main heat load was chosen, yet with a soft shoulder on the backside to avoid leading edges.
A flat extension of the divertor target along the long side of the probe head seems intuitive at first, however at deeper insertion depths the slightly protruding corner on the inner side limits the insertion by high local heat loads. Although more of a concern for the cooled probe head, heat loads at such a corner would lead to overheating more rapidly than in a central part, while for the uncooled probe the diagnostic access would be limited. Therefore, the design with a flattened corner was chosen. The heat load patterns of all magnetic reference configurations can be seen in Figure 4, where the center of the probe head mostly experiences the highest heat load, with some excursions to either side of the top surface.

4. Summary and Future Work

The focus of the next iteration of divertor target manipulators at Wendelstein 7-X are long-term PMI processes, which have to be investigated with scrutiny. The first stage of the inertially cooled DIMS design includes embedded high resolution diagnostics to achieve reasonable agreement with external observation and confidence with the DIMS operation. The observation and active spectroscopy methods allow high quality in-situ analysis, while the whole diagnostic coverage and the rapid probe exchange ensures ex-situ analysis of samples with high throughput and well characterized exposure conditions. The steady-state $10\,\mathrm{MW/m}^2$ design limit of the water cooled probe head in the second stage should enable the investigation of all relevant transient and long-term effects for new materials, components and diagnostics.

The prototype design phase of the first DIMS stage is scheduled to end in 2018/early 2019, giving enough time for elaborate testing and review in 2019. While the probe head design feedback will be more strongly influenced by OP1.2b data analysis, the development and construction of drive train, exchange chamber and supporting structures is receiving feedback by the MPM-operation already and can hence be pursued in parallel.

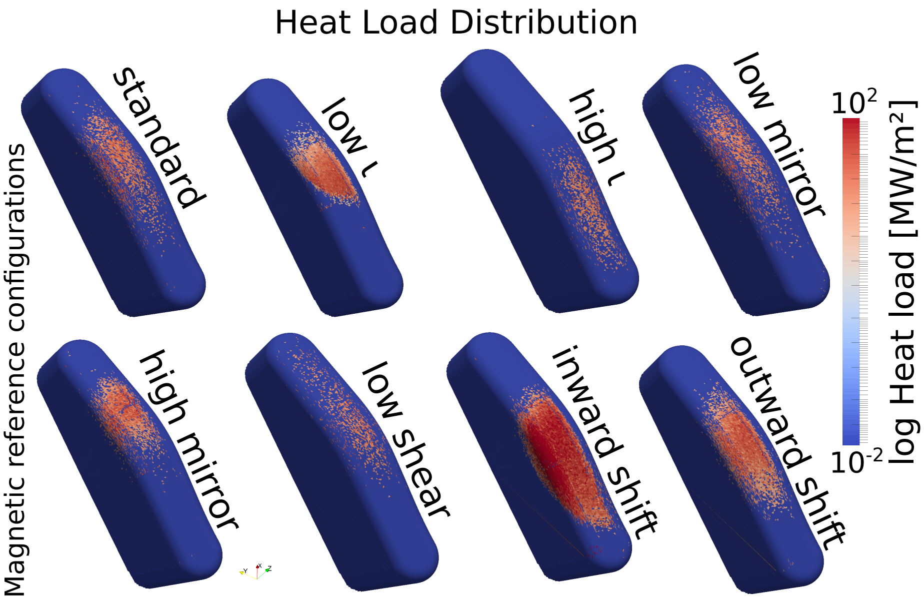

Figure 4: Heat load distribution on probe head for all magnetic reference configurations. Insertion depth chosen to limit peak heat load to below 100 MW/m^2.

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