Development of infrared and visible endoscope as the safety diagnostic for steady-state operation of Wendelstein 7-X

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Magnetic fusion experiments need to demonstrate a safe and robust plasma environment, which can be utilized for energy production. Very important here is durability of the plasma facing components, which will be exposed to high power loads during steady-state discharges. One of the main aims of Wendelstein 7-X is an investigation of quasi-steady state operation, at which up to 10 MW of ECRH heating will be used in the discharges with duration of 30 minutes (24 MW for 10 s). The predominant fraction of the energy lost from the confined plasma will be taken by the ten specially designed discrete island divertor modules. Due to low shear and large island site the island divertor concept is well suited for heat and particle exhaust [1]. Three dimensional

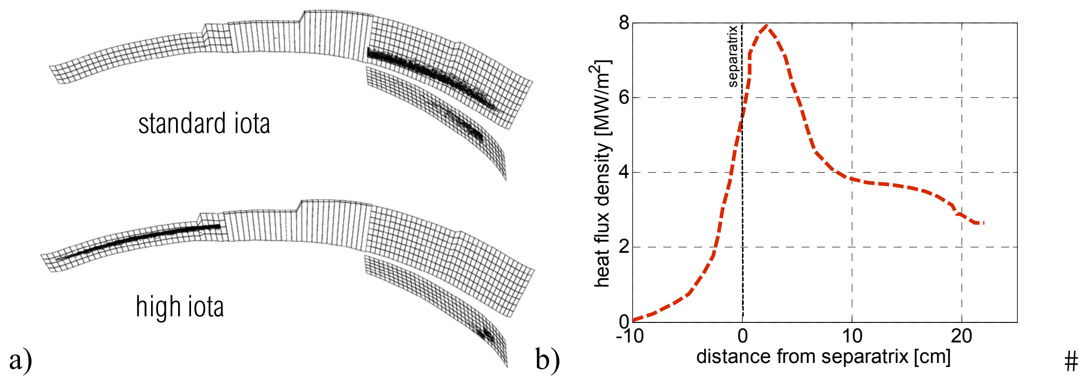

Figure 1 a) Wetted areas of Wendelestein 7-X divertor at two different configurations. b) Structure of the strike line calculated with EMC3-Eirene [cite Y.Feng] at one of the divertor locations.

nature of the divertor wetted area is presented in Figure 1. In contrast to tokamaks, the wetted area is not toroidally symmetric and depends on chosen equilibrium. Typical case for Wendelstein 7-X shown in Figure 1(b) shows a wetted area of order of 10 cm with maximum of about 8 MW/m^2 near the separatrix.

The divertors at Wendelstein 7-X are composed of high heat load target tiles, which can sustain up to 10 MW/m^2 and a lower heat load baffle structure designed for up to 0.5 MW/m^2 power loads. The high heat load targets consist of up to 500 mm long and 50 mm wide individual target elements which are covered with an on average 6 mm thick CFC top layer. This layer is connected via a copper interlayer to an underlying CuCrZr cooling block. To maintain its functionality the interlayer as well as the CuCrZr block may not exceed temperatures of 475 °C. In case local loads exceed this value, there is a risk of delamination and failure of these components, whose plasma facing surfaces consist of carbon fiber composite (CFC). Because of this limitation a close control of the target tile temperature is of utmost importance. The main diagnostic to assure safe divertor operation of Wendelstein 7-X is a set of ten endoscopes monitoring the divertor and baffles surface and the plasma radiation near their surface in infrared and VIS light. The main tasks for the endoscopes is to identify areas with too high temperature and distinguish them from other effects like e.g. surface layers; study the asymmetries in power loads between the W7-X modules and of course power and particle exhaust. Such diagnostic in the environment of Wendelstein 7-X has very high demands as compared to diagnostics in present day short pulse devices.

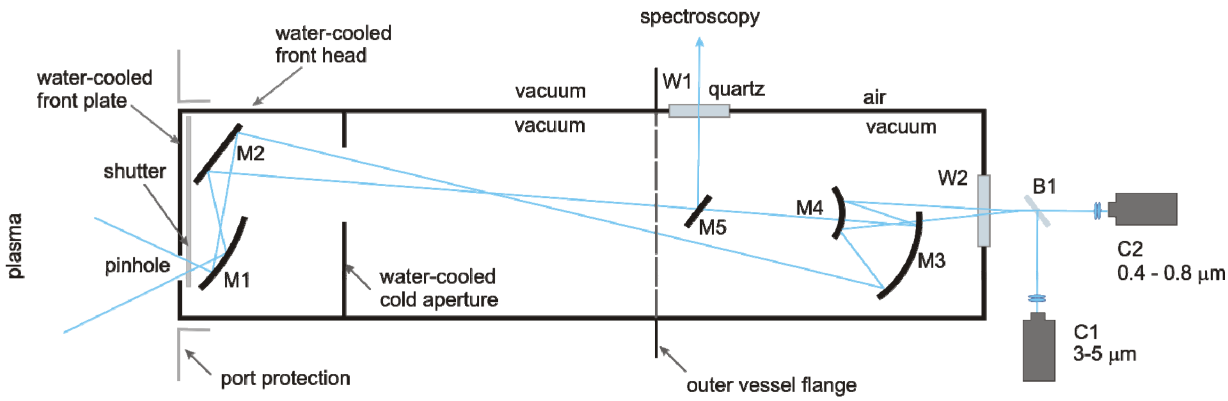

Figure 2. Functional sketch of the IR/VIS endoscope with its main components: M1 - heated, ellipsoid mirror, M2-flat mirror, M3,M4 - off-axis Cassegrain mirrors, M5 - flat mirror, W1-W3 - windows, B1 - dichroic beam splitter, C1 - fast, infrared camera, C2 – visible camera.

Each endoscope is equipped with a complex system of mirrors and lenses, allowing the observation of the divertor surface in infrared (3 – 5 μm) and visible (350 – 800 nm) light. Photons enter inside the endoscope through a pinhole and are directed via two mirrors (M1, M2 in **Figure 2**) onto the off-axis Cassegrain optical system (M3, M4). Off-axis design helps to avoid diffraction due to central obscuration (typical for a Cassegrain system), which would deteriorate the quality of the image. From the M4 mirror light goes out through the window W2, where it is divided by the dichroic beam splitter (B1) into visible and infrared beam and after passing through a set of correcting lenses it is detected by the sensors in cameras (C1 and C2). The whole optical system is designed to observe the 4 m long and 1 m wide divertor with a resolution of up to 6 mm [2], therefore it needs state of the art infrared cameras with sensor resolution of 1280x1024 pixels. The same image, which is transferred via complex optics to an infra-red and to a visible camera is also guided through a separate channel (including mirror M5 and window W1 to the spectrometers for plasma edge studies in UV/VIS range. The W7-X ECRH system can provide 10 MW of heating power for up to 30 min. In X2 mode, this radiation is well absorbed by the plasma for densities below the cut-off density of 1.25×10^{20} m^{-3}. However, for higher densities non-absorbed power fraction can be of the order of 20% or even higher, which leads to ECRH stray radiation of up to 100 kW/m^2 near the endoscope port [3]. Therefore the diagnostic cannot operate with a front window, as it would heat up, which would make infrared measurements impossible and could even lead to a damage of the first window. The entering ECRH stray radiation through a pinhole with diameter of 10 mm is of order of 8 W, which can lead to significant thermal loads on sensitive components during a 30 minutes long discharge. A large fraction of the radiation will be transferred to the camera via the optical system, which could damage the sensor. Unfortunately, neither metal mesh (due to image deterioration)) nor special coatings (exist only for visible range) could not be used. However, between last mirror and the camera sensor there is many optical elements, which might sufficiently absorb the stray radiation. As the absorption coefficients of stainless steel is only of order of few percent, the rest of the stray radiation will form an equilibrium inside the endoscope, as it will undergo a very large number of reflections from the surface until it is finally absorbed.

Any element with higher than stainless steel absorption coefficient will receive significant fraction of the power, which entered inside the endoscope. To minimize that problem a water-cooled element, so-called “cold aperture”, coated with Al2O3/TiO2 (with absorption coefficient of 70% for ECRH stray radiation) is installed inside the endoscope (see Figure 1). Choosing a pinhole instead of a window means that a constant influx of plasma impurities will enter inside the endoscope, which will result in the degradation of the optical system transmission due to deposition of a:C-H layers (especially on the surface of the first mirror – M1). Nevertheless choice of a pinhole over front window seems to be optimal, as loss of reflectivity of a mirror is usually lower than loss in transmission of a window for the same coating. Additionally several mitigation measures are applied in order to cope with this issue. The most important is a shutter, which will keep the pinhole closed in between the discharges. Inside the shutter a ceramic heater (made of Si_3N_4) is installed for regular transmission monitoring. It will be on a weekly basis heated up to 500°C with its temperature measured by a thermocouple and the infrared camera at the same time. Changes in detected by the IR camera surface temperature will allow us to estimate transmission changes of the whole optical system. During a discharge the ceramic heater will be hidden in a stainless steel pocked in order to avoid exposure to ECRH stray radiation. As most of the incoming impurities will be depositied on the first mirror (M1), it will be equipped with a heater mounted on a back side. As shown in [4], heating it up to 400°C will allow to remove most of the deposited a:C-H layers. Additionally we want to test the effectiveness of a flow of hydrogen gas through the observation pinhole on the amount of layers formed on the first mirror.

During long pulse operation the head of the endoscope will be constantly thermally loaded by up to 100 kW/m^2 of power from the plasma radiation. Therefore, the front part of the endoscope needs to be actively cooled in order to keep the endoscope housing at temperatures well below 150°C. Otherwise it would make infrared monitoring of the divertor surface very difficult and could even lead to damage of some of its components. The diagnostic water-cooling circuit with water at the pressure of 25 bar will be used to remove the power from the endoscope head and the cold aperture.

In summary, the design of the steady-state diagnostic for fusion relevant experiments requires careful analysis of the operational conditions. For the IR/VIS endoscope at Wendelstein 7-X the influence of not absorbed ECRH stray radiation, power loads on the front heat of the endoscope and influx of impurities inside the endoscope through a pinhole needs to be taken into account. It is at the moment unclear, if we also need to protect the camera against neutrons produced during discharges with deuterium as a working gas.

[1] K. Mccormick, et al., Journal of Nuclear Materials **313-316**, 1131–1140 (2003).

[2] R. König, et al., Review of Scientific Instruments **77**, 10F121 (2006).

[3] R. König, et al., The Review of Scientific Instruments **83**, 10D730 (2012).

[4] K. Maruyama, Journal of Nuclear Materials **264**, 56 (1999).