Status of the Diagnostics Development for the First Operation Phase of the Stellarator Wendelstein 7-X [a)]

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An overview on the diagnostics which a essential for the first operation phase of Wendelstein 7-X and the set of diagnostics expected to be ready for operation at this time is given, as well as a report on the ongoing investigations how to cope with high levels of ECRH stray radiation in UV/visible/IR optical diagnostics.

I. Introduction

The commissioning phase of the superconducting stellarator Wendelstein 7-X (W7-X)[1,2] has just started and the first plasma operation period (OP1.1) of 3 months duration is expected to begin in about a year's time. At the start of this operation period all in-vessel components will already be installed, except for the uncooled divertor, the heat shield like baffle structure and the carbon tiles not yet being attached onto the heat shields. In this very first operation phase a set of 5 uncooled inboard poloidal fine corn graphite limiters and a specially selected limiter configuration will insure the protection of all in-vessel components. The OP1.1 operation phase will allow an early commissioning and demonstration of the operation of the control and safety systems for the W7-X device components, like vacuum system, cryogenics, magnetic field coils, ECRH heating. Moreover, most of the diagnostics systems will be commissioned and tested for OP1.2, expected to start in summer 2016, albeit them not yet being fully integrated into the standard W7-X data acquisition and control system at this time. Assuming the heat loads can be spread out evenly across the limiters, e.g. 1 second discharges at 2 MW of heating power (ECRH) could be achieved. These pulse parameters will be sufficient to demonstrate the readiness of the installed diagnostics and even to run a first physics program[2], albeit restricted to limiter configurations only.

II. Diagnostics for OP1.1

A. Essential Diagnostics

A set of 6 diagnostics has been defined as essential for OP1.1: The neutron counters are required to obtain the operation license for W7-X. They will be calibrated just before closing the plasma vessel (early 2015), using an in-vessel railway to transport the ^{241}Am/Be calibration source[3]. Flux surface measurements will be taken from the moment we start energising the superconducting coils, in order to learn how to correct any residual error fields with the trim

coils and to gather information how to correct for the effects resulting from the deformation of the coils with increasing field strengths. At the end of OP1.1 it is foreseen to remove the limiters, so that , with the divertors not yet installed, this will give the unique opportunity to investigate the edge magnetic island structures which are essential for divertor operation. The l.o.s. averaged electron density will be provided by a single channel dispersion interferometer with an FPGA based data analysis. We aim at demonstrating the real time capabilities of this system, but without the gas feedback loop yet being implemented. The electron temperature will be provided by a 16 channel ECE system, with an additional set of 16 zoom channels. The limiters are equipped with thermo-couples to ensure that the temperature of the support structure does not exceed a critical value in a sequence of pulses. One of the limiters will be equipped with Langmuir probes as well. 10 simplified (not long pulse compatible) IR/visible divertor observation systems will be used to monitor the limiters loads. These systems will be equipped with 10 NIR ($\lambda \sim 1 \mu m$) and 10 visible cameras fitted with various interference filters (Hα, C II, C II, C III). For OP1.2 two of the 10 systems will be replaced by long pulse compatible endoscopes presently being developed by Thales-SESO. In the remaining 8 simplified systems the NIR cameras will be replaced by 1024x1024 pixel μ-bolometer cameras. The tender for these magnetic field hardened cameras has just been launched. Both systems are covering the entire divertor ($\sim 115° \times 60°$ viewing angle) and are expected to reach a resolution of 6 mm at the low iota end of the divertor and ≤ 10 mm at the far end of the divertor.

B. Diagnostics expected to be ready for OP1.1

A significant number of further diagnostics are expected (though not fully guaranteed) to be available for first operation in OP1.1.
Thomson Scattering, Pulse Height Analysis (PHA), density profile reflectometry, poloidal correlation reflectometry and a new steering Doppler reflectometry system[4] will provide electron temperatures and densities, while the information on the ion temperatures and impurities will be provided by two X-ray imaging systems, the HEXOS VUV spectrometer system[5] (which has already been operated at TEXTOR with a W7-X Mini-CoDaC system and which has already been installed in its final position at W7-X), at least one of two bolometer cameras and a single l.o.s. visible Bremsstrahlung Z_{eff} observation system. The complete set of magnetics consisting of 3 diamagnetic loops, 3 continuous and 2 segmented Rogowski coils, 20 saddle coils and 124 distributed Mirnov coils, have already been fully installed inside the plasma vessel. For the latter two coil systems, the data acquisition may not yet be available in time for OP1.1. Furthermore, the first 5 of 24 neutral pressure gauges in the torus midplane will be installed, as well as a midplane multi-purpose manipulator, the head initially equipped with Langmuir probes and magnetic sensors, combined with a piezo controlled impurity gas inlet. Two 5-nozzles thermal He-beam gas injection boxes, of which one has already been installed on W7-X, will be used for Helium gas fuelling in OP1.1, but also first He-beam spectra will be observed via a window attached to a port lid. The actual He-beam and visible divertor spectroscopy systems, consisting of 2 sets of two scanning endoscopes, looking approximately tangentially and perpendicular onto the target surface at one upper and one lower divertor at the location where the He-beams are integrated into the divertor target plate, will be only available for OP1.2. To investigate the ECRH stray radiation distribution in W7-X, 5 sniffer probes at 5 toroidal locations in the W7-X midplane will be used, as well as a few ECRH bolometers installed deep inside ports to verify the stray radiation distribution model.

II. Coping with ECRH stray radiation in UV and IR sensitive optical diagnostic

One possibility to protect optical diagnostics from being affected by high levels of ECRH stray radiation is to use suitable metal meshes, also in combination with a special ECRH absorbing Al_2O_3/TiO_2 coating on surrounding surfaces, as is being applied in the W7-X

bolometer systems[6,7] . However, in high spatially resolving systems, in particular in high resolution UV/Visible/IR imaging camera systems, the stray light on the grid structure can severely limit the achievable spatial resolution. For the visible spectral range we have demonstrated that the transparent conductive coating ITO (indium tin oxide) applied to an optical window can be used to sufficiently reduce the ECRH transmission (1.2 µm ITO layer: T_{ECRH} <0.5% with T_{vis} between 60% and 90% for λ between 420 nm and 1.4 µm[8]. By suitable sample treatment during the coating production it might be possible to extend the spectral range into the UV[9], but it has not yet been tried to reproduce this effect.

A. Single-wall carbon nanotube (SW-CNT) coating

L. Hu et al.[9] have shown that with SW-CNT coatings it should be possible to achieve transmission coefficients of T > 50% for λ > 200 nm and T > 90% for 2µm < λ < 13 µm while at the same time reducing the 140 GHz (λ=2 mm) ECRH stray radiation transmission by about two orders of magnitude. As a first test the IWS Fraunhofer Institute, Dresden (Germany), prepared sample windows using commercially available SW-CNTs from Nanolab and from IWS Fraunhofer itself. The electrical conductivity of the SW-CNTs layers made from Fraunhofer CNTs were found to be 10-80 times higher, varying with surface density, than when using the ones from Nanolab. Therefore we concentrated our further investigations on the SW-CNTs made by Fraunhofer. Testing a set of samples in our ECRH lab, we found that in order to limit the ECRH transmission at 140 GHz to less than 1.5% one would require a surface density of 3g/m2, corresponding to a sheet thickness of 2.2µm, at which the resistivity would be 3-5 Ω/sq. For these values the IR transmission at λ=2.5 µm would only be 3.5% and at 3-5 µm only be 1.5%. These values are very much different from those with which L. Hu et al.[10] achieved a 60 times better IR transmission (layer thickness 25 nm, resistivity 200 Ω/sq and ECRH transmission T_{ECRH} < 1.5%). The SW-CNT "quality" is extremely important and requires further investigation.

B. IR/visible long pulse compatible divertor observation endoscopes

For the IR/vis. endoscope system the effect of the ECRH stray radiation on the IR detector has been estimated. The optical system has a small 6 mm dia. entrance pupil (pinhole), followed by an aspheric and a planar mirror guiding the radiation to an off-axis Cassegrain system which reflects the radiation to outside the vacuum barrier, where a lens system forms an image of the divertor on a 3-5 µm IR camera. Of the expected 100 kW/m^2 ECRH stray radiation about 3 W will penetrate through the pinhole, of which ~50% will be absorbed at Al_2O_3/TiO_2 absorber coated apertures and tube sections. The other half will be reflected by the metal mirrors and transported through the vacuum window. Behind the intermediate image formed by last metal mirror, the ECRH radiation diverges, since the following imaging lenses have no focussing effect at this wavelength. Due to the geometry of the setup, this results in a reduction of the ECRH stray radiation at the detector by a factor of 120. An additional ~20% absorption can be expected within the lens system (loss tangent values at 140 GHz have been reported by various authors for many UV/vis./IR optical materials[11-13]). The remaining ECRH stray radiation at the detector amounts to ~10 mW distributed over 1280x1024 pixels or 0.007 µW/pixel. This would correspond to a temperature increase at a pixel of the order of $\Delta T \approx 0.004$ K per 1 s (if fully absorbed), which is well within the cooling capability of the Stirling cooler attached to the sensor.

XII. REFERENCES

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