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Topic: EXD

Diagnostic set-up and modelling for investigation of synergy between 3D edge physics and plasma-wall interactions on Wendelstein 7-X

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Abstract: A group of edge diagnostics and modelling has been developed for investigation of synergy between 3D edge physics and plasma-wall interactions on Wendelstein 7-X. A set of endoscopes has been designed for visible and ultraviolet spectroscopy and tomography of the plasma edge, along with infrared thermography of the divertor tiles. Two-dimensional profiles of impurities (e.g. He, C) will be measured by two endoscopes viewing the island divertor region in the plasma edge with a spatial resolution of <2mm. A multipurpose manipulator, which is used as the carrier either of the probe head for measuring the plasma edge profiles or of samples for plasma exposure studies, has been installed at the outside mid-plane on W7-X in 2015. A poloidal correlation reflectometer has been installed at W7-X. The system consists of an antennae array observing the propagation of turbulent phenomena in the mid-plane. The EMC3-EIRENE code package has been adapted for plasma edge transport in helium plasma at Wendelstein 7-X using a hybrid fluid–kinetic approach by enabling EMC3 to treat non-hydrogen isotopes and extending the usage of EIRENE features within EMC3-EIRENE.

1. Introduction

Steady-state operation of future fusion power plants requires a solution for a tolerable plasma exhaust, including steady-state and transient heat and particle fluxes on plasma-facing components. Recently, applications of the three-dimensional (3D) magnetic topology for controlling the edge plasma transport, stability, and plasma-wall interactions (PWIs) have attracted much attention in fusion research, especially the use of resonant magnetic perturbation coils in tokamaks [1]. To investigate this physics issue, however, it is very likely that a superconducting stellarator device, which allows a long-pulse stable operation with an intrinsic 3D magnetic topology concept, will be of great benefit.

The superconducting stellarator Wendelstein 7-X (W7-X) [2], a drift-optimized stellarator with improved neoclassical confinement, is designed for an initially steady-state plasma operation with a maximum magnetic field strength on axis of 3 T, a major radius of $R_0 = 5.5$ m and an effective minor radius of $<a> = 0.55$ m. One major objective of W7-X experiment is to demonstrate steady-state divertor operation at high densities and high central temperatures. Therefore, investigation of the role of 3D divertor concepts in the physics and control of edge transport and stabilities, heat and particle exhausts is essential.

In fact, plasma operation of W7-X follows a staged approach following the successive completion of the in-vessel components. Starting with a limiter configuration, the first W7-X experimental campaign OP1.1 has been successfully carried out. The second campaign OP1.2 has been scheduled in 2017. In this phase, plasma operation with a divertor configuration without water cooling will be implemented, and the total heat power will be upgraded from 5MW (ECRH only) to about 20 MW (ECRH: 8.8MW, NBI: 10MW (D)/ 7MW(H), ICRH: 1.6MW). The main goal of OP1.2 is the preparation of the steady-state phase.

2. Synergy between 3D edge physics and plasma-wall interactions on W7-X

The concept of W7-X for plasma exhaust uses the formation of an inherent separatrix at the boundary for creating a so-called island divertor. The confinement region is either limited by the separatrix of the boundary island chain or by an ergodized region formed by the remnants of overlapping high-order rational islands around the major resonance. Three major island divertor configurations with rotational transform values of ι=5/6, 5/5 and 5/4 are available for use in the coming W7-X experimental campaign OP 1.2.

The PWI in the divertor region of W7-X will be of great importance for the operational phase OP1.2. While the erosion of the divertor will have an impact on its lifetime and is therefore a critical subject of investigation, fundamental PWI studies in the divertor region are in many ways equally significant. These PWIs will be influenced by impurity transport, where the complex 3D magnetic geometry will play a crucial role, but also the magnetic geometry itself will be influenced by plasma effects such as Pfirsch–Schlüter and bootstrap currents. In figure 1, the results calculated by code HINT2 indicate that the width of the edge islands reduced gradually with increase of plasma beta from 0%(vacuum assumption) to 3%. This will directly influence on the distribution of field line connection length and the performance of island divertor. Furthermore, the edge transport and stabilities, impurity screening effect, and plasma-wall interactions will be affected self-consistently. Therefore, along with measurements of obvious quantities such as heat flux,

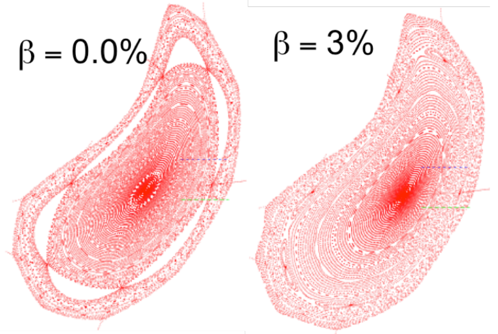

Figure 1 Beta dependence of the magnetic topology on W7-X. Here, the 3D equilibrium is calculated by HINT2 code with a low-iota configuration. The magnetic islands are n/m= 5/6.

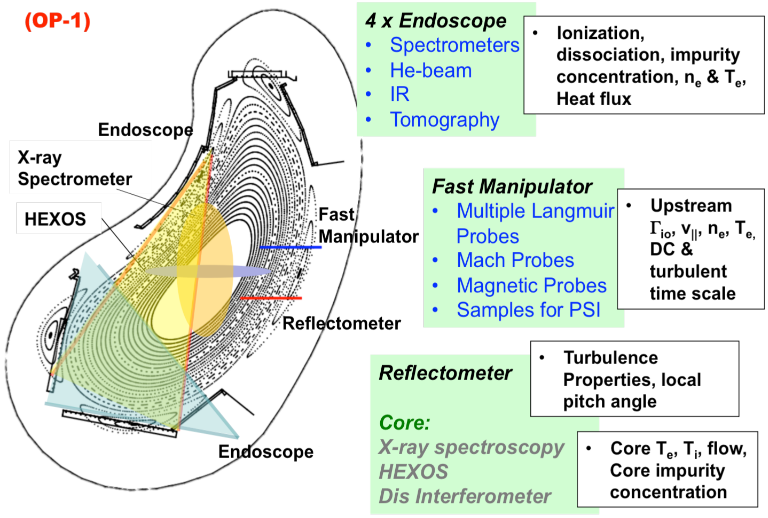

Figure 2 Diagnostics contributed from FZJ during the campaign OP 1.2 on W7-X

PWI research in the divertor region will also require measurements of the temperature in the plasma edge and of the concentration and distribution of different impurities, in combination with modelling of impurity transport.

To investigate systematically the synergy between 3D edge physics and PWI, a set of edge diagnostics [3] (see fig. 2) has been developed for the upcoming W7-X experiments and the EMC3-EIRENE code is being extended to helium plasmas for the OP1.1 phase.

3. Diagnostics set-up and modelling for 3D edge physics and plasma-wall interactions

3.1 Measurements of electron temperature, density, and impurity distributions in the Divertor region, and heat flux on the local divertor target plate

In order to study the impurity origination (C dominate in OP1.2) and edge impurity transport with different magnetic configurations of island divertor on W7-X, a set of endoscopes has been designed for visible and ultraviolet spectroscopy and for tomography of the plasma edge, along with infrared thermography of the divertor tiles [4]. Two-dimensional profiles of impurities (e.g. He, C) will be measured by two endoscopes viewing the island divertor region in the plasma edge with a spatial resolution of <2mm. The working spectral range of each endoscope is from 350 nm to 7000 nm. The light from divertor plasma is divided equally into two branches by prism in detector box. Each branch is divided into ultraviolet (UV: 350 nm – 550 nm), visible (VIS: 550 nm – 950 nm) and infrared (IR: 950 nm – 7000 nm) sub-branches by dichroic filters. Ultraviolet and visible sub-branches are divided again for the filter cameras and spectrometers as seen in Fig.3.

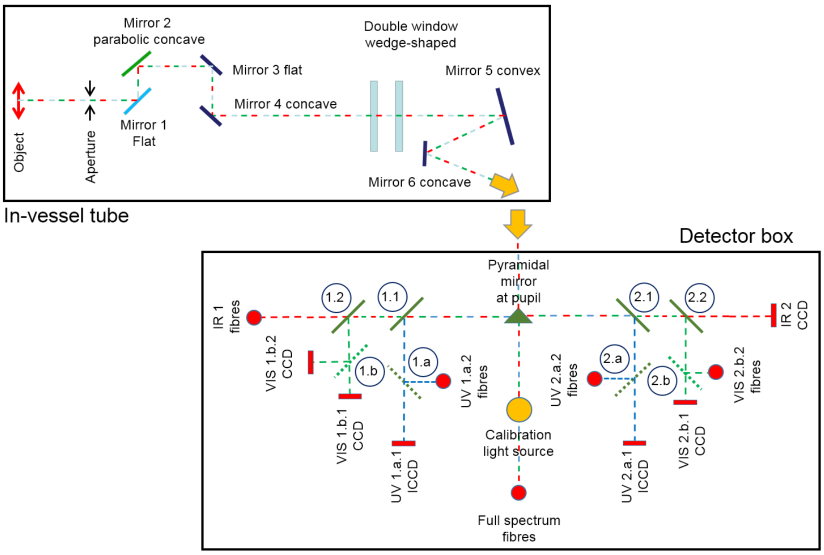

Figure 3 Optical layout of endoscope

Each endoscope includes 5 filter cameras (2 UV and 3 VIS filter cameras), 1 infrared camera and 5 spectrometers (2 UV, 1 VIS, 1 IR and 1 overview spectrometers). The image size on the focal plane is 14 mm x 14 mm, which is focused onto 14 fibers (diameter 1 mm) in array by cylindrical lens. The 14 fibers are connected to the spectrometer located in laboratory. The spatial resolution on divertor plates is 2 cm - 3 cm. Two UV spectrometers are used to measure high-n Balmer spectroscopy to deduce electron density from stark broadening, and electron temperature from line ratio or discrete-to-continuum transition. These two UV spectrometers could be used to measure CD Gerö and C2 Swan band to study the chemical sputtering on carbon divertor plates as well. VIS spectrometer is used to measure Fulcher band to study the hydrogen recycling on divertor plates. VIS spectrometer could be used to measure helium lines to deduce electron density and temperature as well. IR spectrometer is used to measure Paschen series to deduce electron temperature and density.

An overview spectrometer, which can cover wide wavelength range to monitor impurities contents at divertor region, is linked to full spectrum fibers located at the leading edge of the pyramidal mirror in the endoscope system. The light from plasma will be carried by several 1 mm diameter fibers to the diagnostics room, where it will be coupled to the five-channel overview spectrometer (Aventes Model: AVASPEC-ULS2048L-USB2-RM). Each channel is a mini Czerny-Turner spectrometer with fixed grating to cover a certain wavelength range. Together it can cover the wavelength from 300 to 1100 nm. This overview spectrometer will be used for routine investigation of the impurity contents under different operation scenarios. It will also provide reference data for other diagnostics equipped on endoscope system, with which it shares the same field of view.

Through a pair of endoscopes, a divertor high-resolution infrared thermography system (D-IR), which includes two middle wavelength range (3-5 μm) infrared cameras, will be implemented on W7-X to monitor the temperature and to measure the heat flux on both the vertical and horizontal divertor target at one toroidal cross section during in campaign OP 1.2. This D-IR system has a high spatial resolution of less than 2 mm on the divertor target plate, and it would allow for a delicate study of the footprint patterns. With optimized smaller field of view, measurements with high temporal resolution could be achieved to investigate transient events (i.e. Edge localized Modes) releasing large amounts of energy. The designed rotating mirror at the front-end of the endoscope enable the scan of the region of interest, thus the viewing area of the camera has the potential to be actively shifted during the operation for the strike line characterization under different configurations.

The whole endoscope system is currently under construction, and will be installed on W7-X in the end of 2016. A similar system has been successfully applied on JET (the world's largest tokamak) in 2012. In the W7-X experimental campaign OP1.2A, one 0.75m imaging Czerney-Turner spectrometer and two 0.75m Littrow spectrometer will be installed on endoscope. In addition, a high efficiency XUV overview spectrometer (HEXOS) has been used for monitoring impurity concentration in the plasma core.

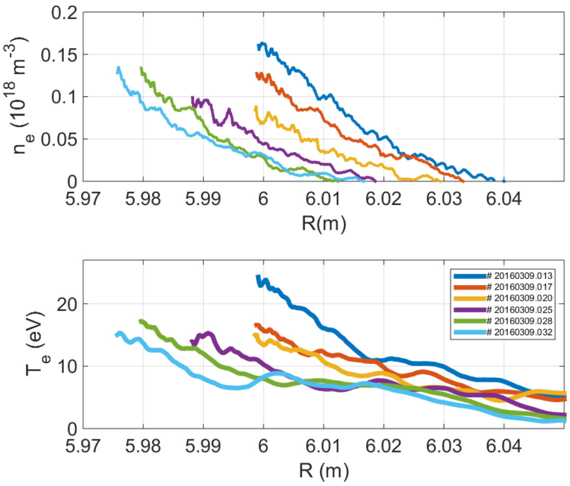

Figure 4 Edge profiles of electron density (ne) and temperature measured by the combined probe on W7-X with various inward shifts high-iota limiter configurations.

3.2 Measurement of edge upstream plasma profiles

A multipurpose manipulator, which is used as the carrier either for measurements of the plasma edge profiles or for plasma exposure studies, has been installed at the outside mid-plane on W7-X in 2015 [5, 6]. One of the most important features of the manipulator is the fast and stable movement of the probe. The maximum acceleration and velocity are 3 g and 4 m/s, respectively. A combined probe head, which measures the radial distribution of the magnetic field with magnetic pick-up coils, the plasma temperature and density profiles with Langmuir Probes and the plasma flows with a Mach Probe, was mounted on the manipulator and commissioned during the campaign OP 1.1 [7]. For the next operational campaign an improved design of the combined probe, a retarding field analyzer (RFA) and a dedicated Mach probe array will be employed. For the plasma wall interaction studies a possibility to expose samples on the combined probe and on a dedicated heatable probe holder is planned.

The combined probe yielded good results in the first campaign, edge profiles of the radial electric field, electron temperature and density and the magnetic field. The probe was able to measure both during a plunge and in stationary position at the plasma edge. A series of scenarios with a tuning of the planar coils and a ramp of the iota was done. These measurements showed that the combined probe is able to reliably measure the edge parameters (see fig. 4).

For plasma edge characterization, measurements of plasma edge parameters, particularly ion parameters, using RFA is a well-known technique, which shown good result on various fusion devices. For W7-X the combined RFA probe head contains two Langmuir pins to measure electron parameters and 2 back-to-back oriented RFA modules to measure the ion parameters simultaneously, each with 3 independent, radial shifted channels (see fig. 5). This combined RFA probe will be mounted on the fast multi-purpose manipulator on W7-X, so that it is possible to determine ion parameter profile through the SOL up to several cm inside the separatrix. By adjusting the applied grid potentials it is not only possible to determine ion parameters, but as well to use the probe head for multi-channel electron parameter measurements or high-energy particle losses measurements.

This probe head has a spatial resolution of 100 µm and radial distance between the channels of 3 mm. Because the combined probe head is optimized for a parameter scan rate of 1 kHz, the radial resolution of 1-2 mm. To ensure that the probe head is always oriented along the magnetic field lines, independent on the choosen magnetic field configuration, it is possible to rotate the probe head manually before the experiment. Due to the high thermal loads, the slit plate for particle flux reduction inside the probe head and for dividing the particle flux into the various channels and also the biased grids are made of tungsten. However, the cover is made of graphite. The design of the combined retarding field analyser has been finalized. First experiments are scheduled for the OP1.2 at W7-X.

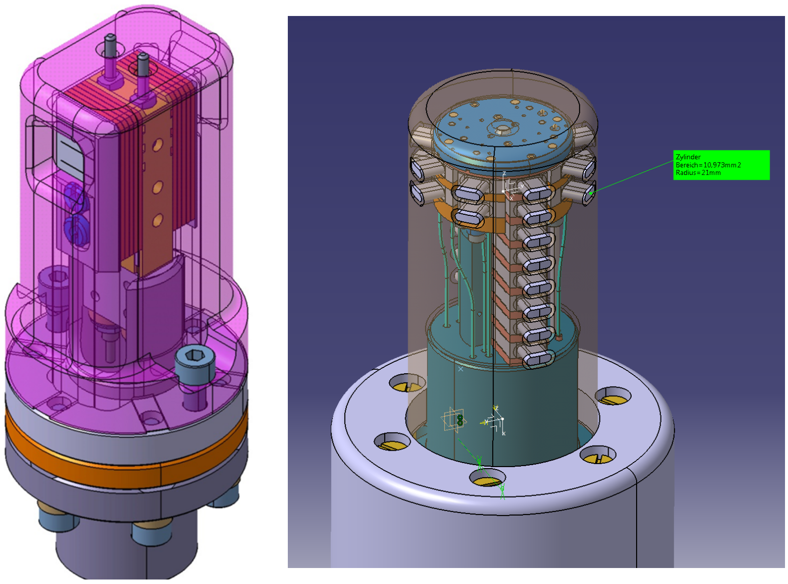

Figure 5 Sketches of the combined RFA probe (left) and the Mach probe (right) for W7-X

To study the dynamic of edge flow profiles with different heating, gas fueling or impurity seeding in the plasmas with various magnetic topology, a multi-array Mach probe, which includes 8 rows in radial direction and 28 pins in total, is under construction for W7-X. Each of top two rows includes 8 pins evenly distributed around the cylindrical probe, while other six rows includes 2 back-to-back pins each, and they are oriented along the magnetic field lines. Each probe pin is made out of tungsten and has a collecting area of 12 mm^2. Moreover the multi-array Mach probe measures edge profiles of particle fluxes with a high temporal resolution of few hundred kHz. Therefore, characterization of edge transport for transient events is possible.

3.3 Measurements of edge turbulence and pinch angle of the filed line

Edge turbulence characteristics can be obtained by the Langmuir Probes on the combined probe head, such as turbulence decorrelation time, cross correlation relationship and turbulence propagation along both poloidal and radial directions, phase velocity, particle flux driven by turbulence and Reynolds stress. During the campaign Op1.1 the typical poloidal correlation length of turbulence is about 1-2.5cm in the SOL region, and decreases to ~1cm inside the LCFS. Figure 6 shows a typical auto power spectrum from floating potential measured by Langmuir probes, with discharge conditions of the line averaged density $<n_e> = 2.4 \times 10^{19}$ m^{-3}, ECRH heating power P=4 MW and the standard limiter configuration. A near 7 kHz mode is observed as shown in figure 1. This mode can be detected at R=6.11m, about 10 cm outside of the LCFS, and its amplitude increases significantly when close to the separatrix. It should be noted that the magnetic coils embedded in the combined probe head also measured this 7 kHz mode.

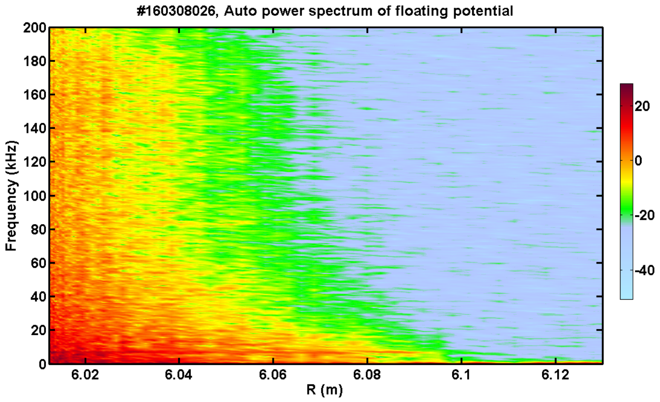

Figure 6 Auto power spectrum of the edge floating potential measured by Langmuir probes on W7-X with a limiter configuration.

A poloidal correlation reflectometer has been installed at W7-X [8]. The system consists of an antennae array observing the propagation of turbulent phenomena in the midplane. The diagnostic operates in a bean shaped poloidal plasma cross section. The five antennae aim at the plasma center. The system is operated in O-mode polarization which limits the observation range to those reflection layers (r_c) which fulfill the condition $n_e(r_c) < 2 \times 10^{19} m^{-3}$. Beside the spectral characterization of the turbulence the system is capable to measure the poloidal propagation of the turbulence from 6 different antenna combinations.

Moreover the poloidal and toroidal separation of the system allows to measure the inclination angle of the turbulence. Knowing that the turbulence is aligned to the magnetic field line, the pitch of the magnetic field line can be calculated. Deviation from the magnetic field line pitch can be considered to be caused by limited toroidal correlation length of the investigated turbulence. Furthermore it will be tried to measure the pitch in the vicinity of the of the island divertor. The pitch is related to the iota in the island. Accessing this quantity enables the measurement of the topological parameter relevant for the flux diversion, the field line connection length. In the island divertor of W7-X this length is calculated from the internal rotational transform inside the island.

Another relevant topic is the existence of zonal flows. Those flows are characterized by a temporal enhancement of the flow velocity can could be determined by the instrument. To be able to measure transient events with sufficient time for averaging the temporal resolution of the diagnostic is 4MHz. This should allow the measurement of velocities in less than 1ms. The system is in operation since December 2015 and data are taken on a daily basis. In addition the reflected signal is used as indication of the achieved plasma density, because the reflection condition depends on the local plasma density.

3.4 Modelling for 3D Edge transport and heat loads distributions

Understanding the plasma exhaust processes in stellarators needs 3D transport models that are capable of dealing with transport processes in a stochastic field where closed flux surfaces do not exist. For this, the 3D plasma edge Monte Carlo code EMC3 will be used in connection with the W7-X island divertor experiments [9].

The fluid edge plasma Monte-Carlo code in three dimensions (EMC3) [10] coupled to the kinetic (neutral) transport code EIRENE [11, 12] is a commonly used plasma edge simulation code for treating complex magnetic configurations. EMC3-EIRENE has been continuously improved and verified, but one remaining restriction up to now was that the bulk ion species is limited to hydrogen isotopes, with higher-Z ions being treated as trace-impurities.

However, in initial operation phases W7-X was operated with helium plasma. Computational quantification of helium plasma flows in the edge is required to extend the understanding of the involved physical processes. Therefore, an approach was studied to simulate helium plasma by slightly extending EMC3 to facilitate a treatment of the main plasma species with Z $\neq$ 1 and expanding the use of EIRENE features within EMC3.

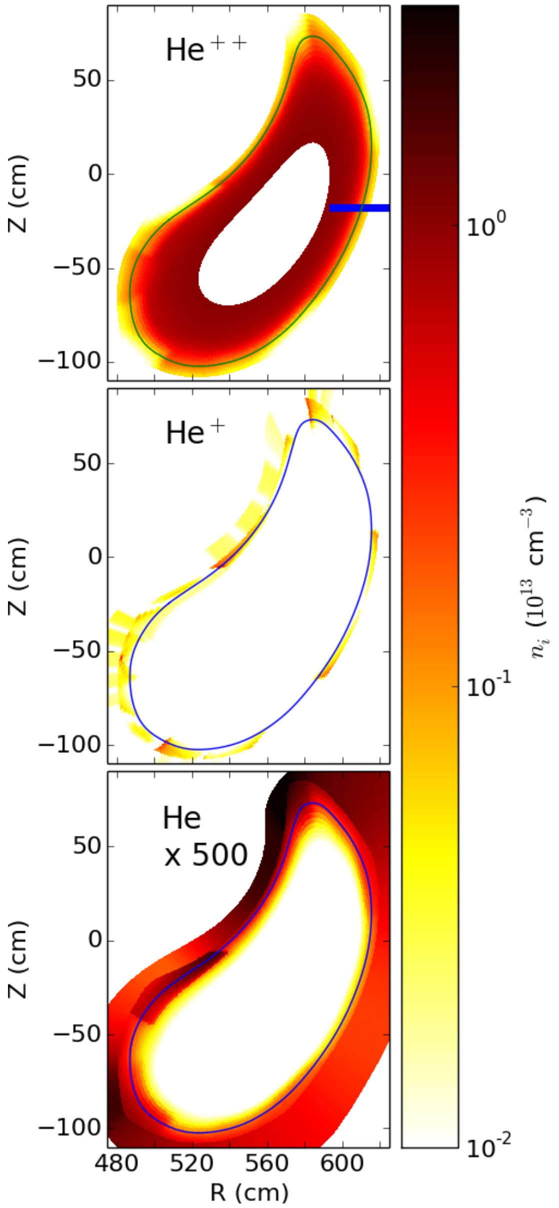

Figure 7 Comparison of neutral helium, He+, and He++ density distributions calculated for a typical W7-X limiter plasma with an averaged upstream ion density of $\langle n_i \rangle_{LCFS}$ = 0.5 × 10^{13} cm^{-3} and a heating power of P = 2MW. The blue line indicates the location of the multi-purpose manipulator and the solid line represents the LCFS.

A zero dimensional estimates of the ionisation and population distribution using collisional-radiative rate coefficients by McWhirter and Hearn [13] and Fujimoto [14] as well as estimated transport losses (via HYDKIN [15]) indicates that a reasonable treatment of helium plasma as a single-fluid system with helium in the second ionisation state is justified for limiter plasmas at W7-X ($n_e > 1 \times 10^{13}$ cm^{-3} and $T_e > 20$eV).

A second estimate on the correct treatment of helium plasma can be made based on EIRENE test simulations by comparing the recycling flux from the targets with fluxes from volume-recombination. The simulations show that the dominant source for He+ ions under the given conditions is ionisation from helium atoms rather than volume-recombination from He++ ions. Thus, it leads to the same conclusion as the zero-dimensional estimate: helium in the second ionisation state is dominant in the bulk of the plasma edge. Furthermore, this can be strengthened by comparing the simulated spatial distribution of neutral helium, He+, and He++ in a typical limiter discharge at W7-X (see fig. 7). Here, shown for a poloidal cross-section similar to that seen by the multipurpose manipulator.

A treatment of neutral helium and He+ ions is also required for a sufficient consideration of plasma wall interactions, which can be performed using the kinetic transport code EIRENE. In the simplest approach, the He+ ions can be considered to have a distribution function that is a general solution of the Boltzmann equation. Therefore, an adequate treatment of He+ ions is drift kinetic, incorporating transport effects at least at a certain level. The simplest transport model employed consists of following the He+ ions in the test particle picture. Trajectory integration is carried out in the guiding centre approximation, ignoring drift motion or anomalous transport. Processes like He–He+ charge-exchange are considered via the non-linear collision model of EIRENE. The dominant ion species He++ is treated with the fluid approach using a generalized model for EMC3 allowing for non-hydrogen isotopes.

4. Summary

Synergy between edge and divertor physics and Plasma–wall interaction (PWI) will be of great importance for operational phase OP1.2, in which various island divertor configurations will be applied for the first time on W7-X. These plasma–wall interactions will be influenced by impurity transport, where the complex 3D magnetic geometry will play a crucial role, but this magnetic geometry could itself be influenced by plasma effects. Therefore, In order to investigate systematically the synergy between 3D edge physics and the PWI, a group of edge diagnostics and modeling has been developed in combination with modelling of impurity transport on W7-X.

5. Acknowledgments

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