Microwave and Interferometer Diagnostics for Wendelstein 7-X

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For the superconducting stellarator Wendelstein 7-X (W7-X) [1], to be operated in Greifswald, Germany, a pulse length of 30 min at 10 MW ECR heating is planned. The expected cw heat load at diagnostic frontends is around 100 kW/m^2, which requires active cooling. Microwave diagnostics use in-vessel stainless steel optics and Cu waveguide components - the latter only if direct plasma radiation can be avoided - providing therefore the possibility for operation with high heat- and particle loads even under steady-state and reactor relevant conditions. Sensitive microwave receivers can be installed outside the radiation shield, connected through oversized low-loss transmission lines of about 20 m length in order to allow accessibility during magnet operation. Steady state ECR heating at 140 GHz results in a level of several ten kW/m^2 of nearly isotropic microwave stray radiation in the torus in particular during high density operation, where the absorption of the ECRH beams is less [2]. To cope, adapted notch filters are required in the transmission lines.

W7-X, with a large major radius R=5.5m and rather large aspect ratio R/a~10 offers nearly ideal conditions for microwave diagnostics: The cyclotron resonances are well separated and the curvature of the flux surfaces is only moderate. Moreover, steep density gradients are expected with well localized cut-off layers. The commissioning phase of W7-X just started and the first plasma Operation Period of 3 months duration (OP1.1) is expected to begin in about a year's time. This early operation phase[3] is dedicated to commissioning and testing of the device, its periphery, heating and diagnostics. A configuration with 5 uncooled graphite inboard limiters will be used to protect the already installed in-vessel components. The limiters restrict plasma operation to 2 MJ pulses, e.g. 1 s pulses with 2 MW ECRH, which is sufficient for technical commissioning and even allows the running of a first physics survey. The uncooled Test Divertor Unit, baffle structure and carbon tiles for wall protection will be installed afterwards for the physics exploration phase OP1.2 scheduled about a year later. Only a reduced set of diagnostics[4] will be commissioned before and during OP.1.1. The set of 6 diagnostics considered as essential includes the 32-channel ECE system and the single-channel interferometer, which are both necessary to develop reliable plasma start up, heating- and EC current drive scenarios. However, the first reflectometers will also be tested.

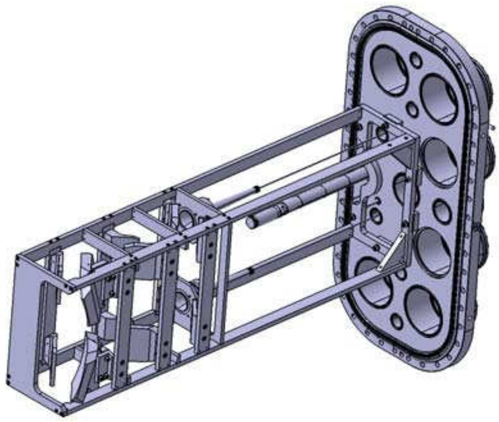
ECE will measure the electron temperature profile using the 2nd harmonic x-mode emission in the frequency band 126 GHz to 162 GHz at 2.5 T operation. Spatial resolution is maximized by minimizing the emitting volume for each frequency interval, i.e. a line of sight perpendicular to the flux surfaces and a slim Gaussian antenna characteristic focused at the plasma center with a FWHM of <30mm along the signal path through the plasma. The latter is achieved by intrinsically broadband Gaussian beam telescope optics, consisting of 2 elliptical and 2 plain stainless steel mirrors - the latter for beam folding and steering - and an adapted broadband horn antenna. This arrangement also keeps Cu components - microwave horn and waveguides - in the shadow of the mirrors far away from the plasma. The toroidal position has been selected such that the local stellarator magnetic field at the plasma axis differs from the 2.5 T in the ECRH launching plane. Thus the central plasma temperature can also be measured without being masked by the strong 140 GHz microwave stray radiation. The vacuum barrier uses a 100 µm thick Viton sealed mica sheet with 4 mm aperture as broadband vacuum window. A 28 mm diameter oversized circular transmission line with overall length ~22 m guides the 2 mm microwave radiation to the 32-channel ECE radiometer outside the experiment hall. In front of the radiometer the frequency band of stray radiation from the gyrotrons (139.9 to 140.4 GHz) is cut out of the spectrum by a waveguide Bragg reflection >60 dB notch filter [5] with extremely steep edges and an insertion loss of only ~1dB outside this frequency band. The radiometer [6] uses a single broadband mixer for down conversion to an intermediate frequency range centred around 18 GHz and subsequent 2-18 GHz and 18-40 GHz filterbanks, 16 channels each. The bandwidth of the individual filters corresponding to a radial resolution between 1cm to 3cm is adapted to the radial resolution of the ECE emission, as calculated from the optical depth at the expected plasma conditions[7]. For higher radial resolution an additional zoom device[8] allows the selection of any suitable frequency range of the spectrum by the aid of a tunable second local oscillator. In magnetic radial coordinates the selected frequency span of 4 GHz covered with 16 channels corresponds to a radial range of Δr~6cm at the High-Field Side (HFS) or ~15cm at the Low Field Side (LFS), respectively. This zoom device is particularly dedicated to perturbation experiments such as ELM studies or heatwave experiments from which the ECRH power deposition can be determined also. For an overall absolute calibration of the diagnostic a second identical Gaussian optical system is provided as a twin outside the torus including identical waveguide components, mica window and a geometrically identical transmission line, however with a hot-cold calibration source in front of it. A special feature of the ECE diagnostic is a second observation antenna with line-of-sight directed from the High-Field Side across the plasma *towards* the Gaussian optics enabling measurements of the emission from non-thermalized and current drive electrons at the same locations [9]. The received radiation is guided to the next available port with rectangular overmoded waveguides. Outside the vessel this antenna is connected to the ECE radiometer via an oversized transmission line as well.

Interferometry in W7-X cannot use microwaves, which suffer from the long path-lengths through the plasma and space restrictions which do not allow for large optics in opposite ports, as well as from densities in excess of $1 \cdot 10^{20}$ m^{-3} resulting in refraction and multiple reflections. The latter perturb the phase measurement introducing by spurious signal paths.

Instead, Dispersion Interferometry (DI) [10] using a 10.6 μm CO_2-laser and its second harmonic will be used for density control and later density profile measurements. DI employs frequency doubler crystals ($AlGaSe_2$) to create a 5 μm reference signal propagating along the same path such that a separate reference path is not required. The measurement thus becomes independent of geometrical variations of the path length expected e.g. from vibration caused by turbo pumps, water flow in the cooling pipes or long-term thermal drifts. After passing the plasma the 10 μm signal is also up-converted and the phase measurement is performed using the 5 μm signals. As the resulting phase excursions can be made $<2\pi$, DI is an option for tracking the density under steady-state conditions. The single-channel CO_2 DI interferometer shares its sightline with the YAG-laser for the Thomson scattering system which allows for cross-calibration. ZnSe and quartz windows have to be used respectively due to the different wavelength which his makes it necessary that the sightlines are slightly (~3deg) tilted with respect to each other. The 10μm/5μm interferometer beams are back-reflected from a 50 mm diameter retroreflector fastened to the Thomson diagnostic support structure for the in the torus center. The long overall distance between the last launching mirror and retroreflector of ~8m made it necessary to develop a feedback controlled beam steering system to cope with thermal drifts during long pulses. Although it has been shown that DI is intrinsically versus vibrations along the sightline,[11,12] vibrations perpendicular to the line-of sight - modulating misalignment - may result in small phase perturbations[13]. Therefore the DI has been installed on a massive vertical vibration isolated bench that consists of two vertical granite plates held by a massive Al-structure on a vibration isolated concrete base plate. For the phase measurement a heterodyne modulation scheme is used applying an elasto-optical ZnSe modulator at modulation frequency 50kHz, which also determines the temporal resolution. The phase shift is derived from the returning signal by fast direct sampling (125Ms/s) followed by digital filtering, down conversion and phase comparison by a Field Progammable Gate Array (FPGA) which provides data in real time.

A 10 ch DI is being prepared, starting with 4 ch in OP1.2, to track the density profile shape in the core and study the necessity and success of deep fuelling. The W7-X stellarator configuration does not allow for large opposite ports. Instead, high-heatload Mo retroreflectors have been developed which will be incorporated in the tiles of the heatshield.[14]

Reflectometry: Doppler reflectometry will monitor edge density fluctuations and their poloidal propagation velocity. The figure below shows the bistatic broadband (50-110 GHz) Gaussian in-vessel optics attached to one of the large 100cm×40cm port closures. Other diagnostic plugins at this port are not shown. The optics consists of 3 focussing and 3 plane stainless steel mirrors for both launching and receiving and of broadband Gaussian horns each. This not only allows an optimized variation of the spot size ~sqrt(λ) at the reflecting layer[15], but also lets the beam waist position shift deeper into the plasma, as smaller wavelengths are launched to probe higher densities. The optics can be used both in x- and o-mode polarization, which gives flexibility and will later also allow for density profile measurements. Similar to ECE, the reflectometers will be outside the torus hall and connected by oversized circular transmission lines with single pass length ~27m. For start-up a V-band hopping reflectometer[16] is prepared for first Doppler reflectometry studies. For OP1.2 an extension of the system, including an identical reflectometer with optics at a toroidally shifted probing position, is planned and for studies of large scale flow structures.



In addition a fast steering Doppler reflectometry antenna has been developed, capable of fast angular scanning the probing beam, thereby scanning the K-spectrum of turbulence via the Bragg-condition[17]. The antenna consists of 32 stacked H-plane sectoral horns and a phased feed array which allows varyation of the beam tilt angle between ±20 deg by small frequency scans Δf~0.7GHz around 15 frequencies in the W-band, which define the reflecting layers. The plugin will be installed in direct neighbourhood of the Gauss optics plugin, enableing crosschecks. Moreover, a conventional 24-40 GHz poloidal correlation reflectometry plugin with 5 antennas is under construction for measurements around the separatrix, including characterization of density turbulence, edge mode activities and measurement of the relatively low flow velocities expected there. This plugin is also attached to the flange shown, to allow for a cross-calibration of the measured propagation velocities. For OP1.2 planned reflectometry extensions include edge density profile measurements to track the upstream density and characterize the expected steep edge gradients.

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