ECRH Heating Scenarios and In-Vessel Components at the Wendelstein7-X Stellarator

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Abstract. Several ECRH scenarios have been investigated for Wendelstein7-X. Beside the well known standard X2-mode, efficient heating at 140 GHz was found for the O2- as well for the and X3-mode. The ECRH-launching system must satisfy the requirements of a cw operation at the different heating scenarios. Its design and test results of the most critical components will be presented.

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INTRODUCTION

The large super-conducting Wendelstein7-X Stellarator (W7-X) [1], which is under construction in Greifswald (Germany) now, will be equipped with a 10 MW ECRH system at 140 GHz. The ECRH will be the main heating system and the only one, which is capable for CW operation. Therefore, it has to cover a wide experimental parameter range and its components should have a high reliability. The heating scenarios cover the full operation range of W7-X in density. The first two chapters will present the different heating scenarios.

The ECRH scenarios require a highly flexible launching system. Furthermore, the high heat load conditions in cw-operation necessitate a reliable technical solution for the in-vessel components, which can sustain both, the power load of the microwaves and the plasma radiation. Several critical components have already been tested for reliability and heat loading. The design and the tests will be presented in the last two chapters.

X2 HEATING

For plasma start-up and “low” density ($<1.2\ 10^{20}\ m^{-3}$) operation heating with the second harmonic X-mode (X2) is foreseen. Its single pass absorption is sufficiently high that nearly total absorption is guaranteed up to its cut-off density ($<1.2\ 10^{20}\ m^{-3}$). As shown in Figure 1 at low density a plasma temperature of above 10 keV is expected. The heating power of 10 MW should be sufficient to sustain a plasma at 1.0 10^{20} m^{-3} at a temperature of still 4 keV. Although in stellarators neither a permanent ECCD for the plasma confinement nor any NTM- stabilization is needed, the control of the divertor strike point position requires a permanent control of the edge rotational transform iota. Therefore ECCD will be used for residual plasma current compensation and rotational transform control on a fast time scale. For long time scales the iota will be controlled by the currents in the coil system. With the installed power of 10 MW up to 300 kA current could be driven at 1.0 10^{19} m^{-3} by ECCD. Even at 1.0 10^{20} m^{-3} an ECCD current of up to 30 kA was estimated, which is sufficient to compensate the expected boostrap current of about 20 kA. Beside the standard low field side oblique launch, two special ports (N-type) for advanced current drive scenarios are foreseen, where the phase space interaction can be optimized. One beam can be launched through each port along the B=const surface in order to localize the interaction in the phase space.

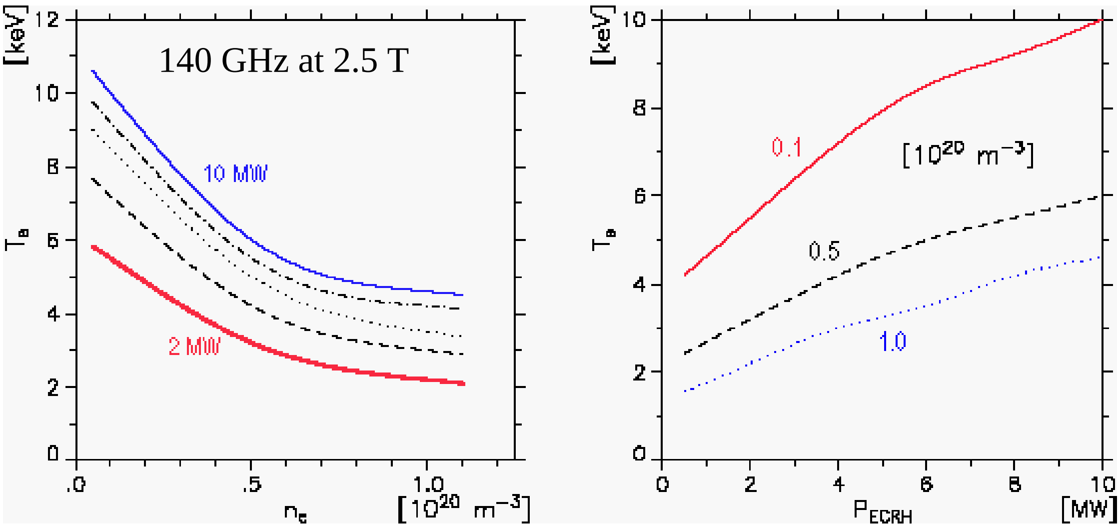

Figure 1, Expected central temperatures for X2-heating as a function of density and heating power.

O2, X3 AND OXB HEATING

At “medium” densities (<2.4 10^{20} m^{-3}) a heating scenario with a multi-pass absorption of the second harmonic O-mode (O2) was developed. Here a single pass absorption of 50-80% is expected as shown in Figure 2. This would thermally overload the standard graphite wall protection tiles in opposite of the ECRH antennas. Therefore 12 selected tiles have been chosen to be replaced by highly reflecting materials like TZM (molybdenum alloy with small amounts of titanium and zirconium). The reflector position and orientation was optimized by ray-tracing calculation, thus that the second pass will be through the plasma center, too. This will increase the heating efficiency significantly and reduce the level of the non-absorbed ECRH stray-radiation drastically. The same reflecting tiles can also be used for the third harmonic X-mode (X3) heating at a magnetic field of 1.7T. The launch angle for both heating scenarios is about 12° only at the most elongated plasma cross-section position. Therefore the beam deflection by plasma refraction is below 3 cm at the tiles, which can be easily compensated by the movable antennas. The beam position as well as the transmitted power will be measured in-tile integrated microwave pick-up horns.

Since stellarators do not suffer upon density limit based on MHD-stability, high density operation above the 140 GHz cut-off (2.4 10^{20} m^{-3}) is expected. Here the use of the OXB-mode conversion heating, which was developed at the Wendelstein7-AS stellarator [2], is foreseen. The required launch angle of 35° is supported by the actual antenna design. First ray-tracing calculation EBW power deposition have been started recently.

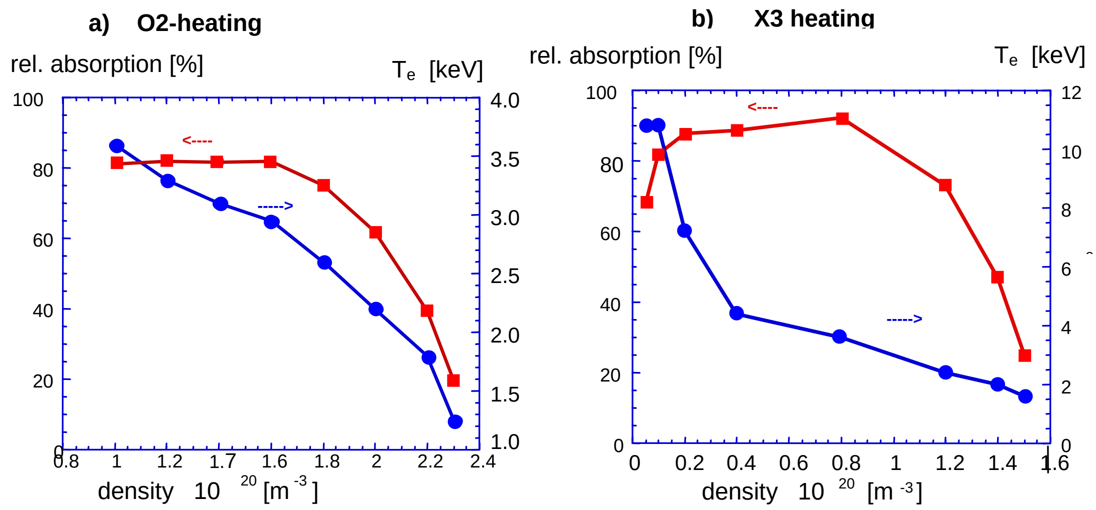

Figure 2. Single pass absorption for the O2-mode (left, squares)) and the X3-mode (right, squares)) as a function of density. The temperature (circles) was estimated according to the stellarator scaling for an input power of 10 MW.

ECRH ANTENNA DEVELOPMENT

The selected heating scenarios require a flexible launcher system. For the low field side launch there are 12 beam lines in 4 large equatorial ports (type A and E) foreseen. Two further beam lines are launched through two lateral N-type ports. Each of the equatorial beams is quasi-optically transmitted through its individual diamond vacuum window towards a fixed focusing mirror and a bi-axially movable steering mirror as shown in Figure 3. The water-cooled tubes, which are screening the beams, are used as the mechanical support for the front mirrors in the plug-in equatorial launcher. Special designed apertures inside the beam tubes prevent backward transmission of any reflected power. The movable mirrors enable a poloidal steering range of ±25° and a toroidal steering range between ±15° and ∓35°. The cooling water of the front steering mirror is feed through two push-pull bars, which are used for the mirror positioning. The joints in the push-pull bar system are bridged by tube spirals as shown in Figure 4. The universal joints are screened by additional copper half shells and the surrounding tube spirals against microwave and plasma radiation. We expect a microwave radiation level of about 500 kW/m^2 and a plasma radiation of 100 kW/m^2. A first launcher mock-up had been build and tested for the push-pull bar positioning and the motor-drive reliability. In a test with 10000 full scan cycles the accuracy of the positioning was found to be 0.05°. The motor drive was also successfully tested in a magnetic field of up to 40 mT, as it is expected at the motor position near the stellarator. The most critical elements are the tube spirals made of stainless steel tubes with 7 and 8 mm diameter and 1 mm wall thickness. Due to the bi-axial mirror movement, they have to withstand both a bending angle of up to 45° and a torsion of 10°. Their maximal tension was calculated by an analytic model. This model was benchmarked by a cycling test of a down-scaled spiral (less windings), which was tested for 10000 cycles with increasing bending angle until the critical tension was reached and the spiral was broken. Based on these results the spirals were designed with a safety margin of about two. They passed the 10000 cycle full range test successfully. It should be mentioned that the spiral were annealed to minimize the internal tension before assembly. Further more, for two types of the spirals the tube circular cross-section was pressed into an elliptical one, in order to avoid the contact of the winding at the maximum bending angle. The measured hydro-mechanical properties of the spirals require a water cooling system of 16 bar. The mock-up launcher is already equipped with the water cooling and is presently prepared for integrated tests in the stray radiation test chamber MISTRAL. For the N-type port launch no detail design is exiting, but a remote steering launcher could be a feasible solution.

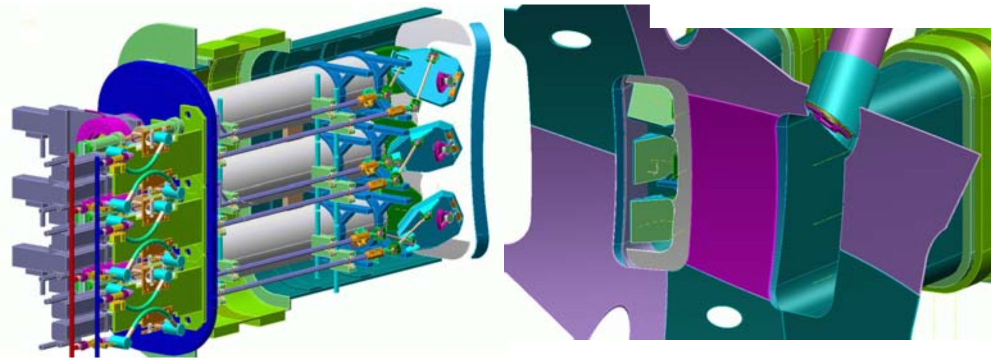

Figure 3. Right: ECRH plug-in launcher for the equatorial port in W7-X. Left: inside port design. Right: front view.

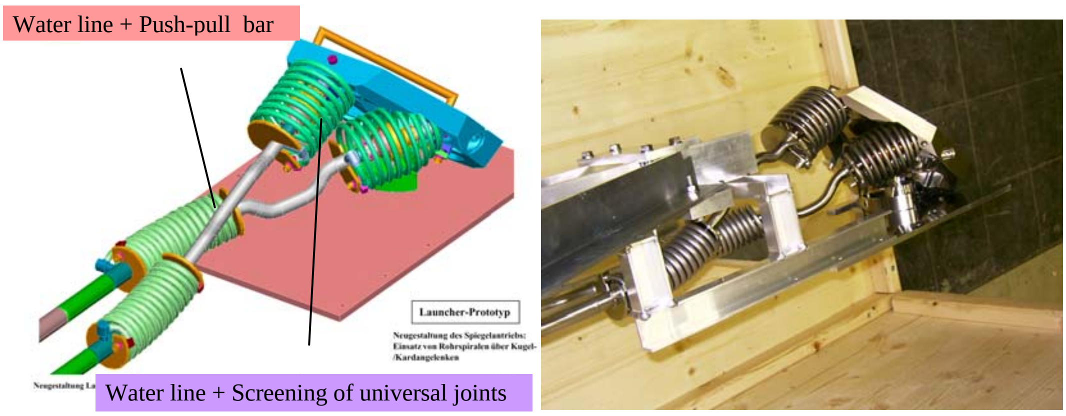

Figure 4. Tube spirals for a flexible cooling water supply of the front steering mirror. Left: CAD. Right: Mechanical realization in the ECRH mock-up launcher.

For the O2 and X3 ECRH scenarios microwave reflectors have to be installed on the inner vessel wall opposite to the steering mirrors (see Figure 5). These tiles consist of a TZM mirror surface, which is clamped on a water cooled copper structure. In addition they are equipped with the transmission measurement pick-up horns, which are incorporated into the tile. Their thermal properties had been simulated for different beam profiles. A test tile has been manufactured and is prepared for high power test now.

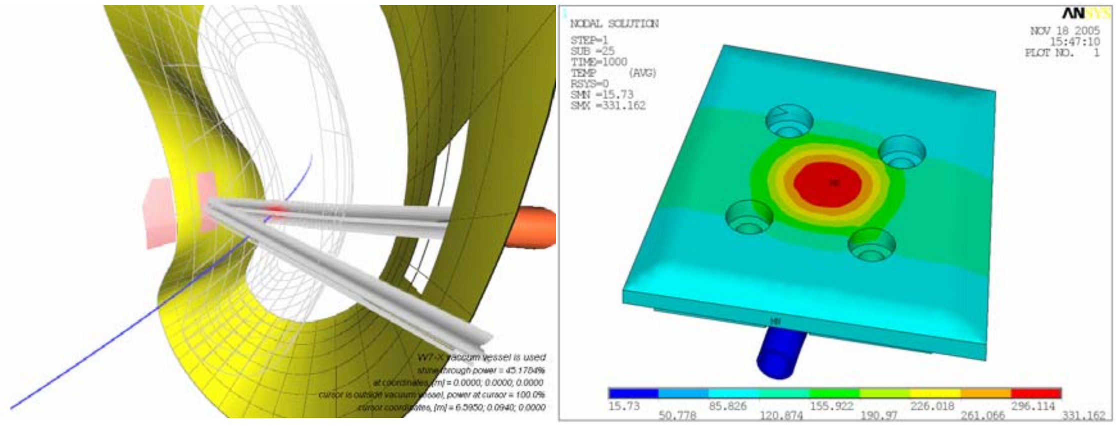

Figure 5. Left:Ray-tracing calculation for the optimum position of the O2 and X3 reflector tiles at the plasma vessel in-board side. Right: Heat load simulation of a strongly focused ECRH- beam (500 kW beam waste 20 mm) at the TZM-reflector tile.

STRAY RADIATION TEST CHAMBER (MISTRAL)

The O2, X3 and OXB ECRH scenarios feature a large microwave stray radiation level inside the stellarator. This stray radiation origins in the non-absorbed power, which was distributed inside the vacuum vessel by multiple reflections. The stray radiation had been modeled with a multi resonator model [3]. This model was already benchmarked with measurement at the FTU-Tokamak and the Wendelstein7-As stellarator. We expect a stray radiation level of 500 kW/m^2 in the antenna ports and 200 kW/m^2 in the Wendelstein7-X moduls 1 and 5, where the ECRH will be launched. The high stray radiation level could thermally overload insufficiently cooled absorbing materials. In addition it could generate small sparks in wavelength resonant structures. Therefore the large stray radiation test chamber MISTRAL was build, in order to enable integrated test of critical W7-X in-vessel components (see Figure 6). MISTRAL is presently powered with an average power of 30 kW by one 140 GHz gyrotron from the W7-AS installation at IPP-Garching. The chamber itself and the scheme of stray radiation generation is shown in Figure 6. In near future the chamber will be transferred the IPP-Greifswald, where one of the high power 140 GHz (1 MW) gyrotrons will generate the required stray radiation field.

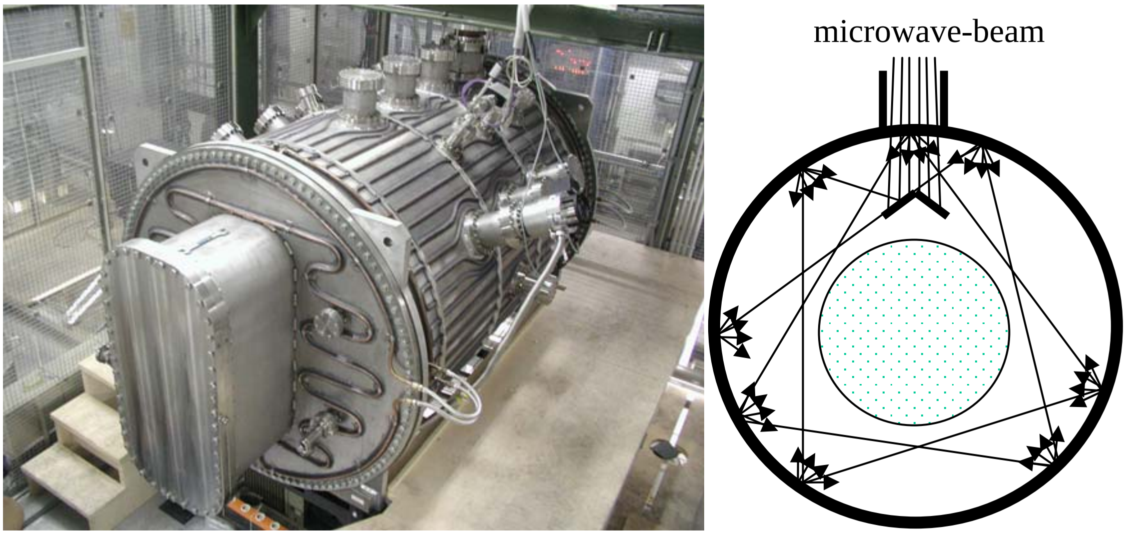

Figure 6. Left: ECRH stray radiation test chamber with a large W7-X equatorial port type A in front. Right: Scheme of stray radiation generation. The microwave beam is rotating in side the test in a whispering gallery mode. Every reflection at the rough in-vessel surface illuminates the shadowed central test volume.

SUMMARY

The ECRH scenarios will cover the full density range for plasma operation, which is foreseen for W7-X. In addition the X3 heating provides an operation at a reduced magnetic field of 1.7 T. The In-Vessel components for W7-X are designed to provide CW operation for all ECRH scenarios. Intensive prototype tests have been performed in order to build a highly reliable system.

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