EUROFUSION WPS1-CP(16) 15711

B Schweer et al.

Development of an ICRH antenna system at W7-X for plasma heating and wall conditioning

Preprint of Paper to be submitted for publication in Proceedings of 29th Symposium on Fusion Technology (SOFT 2016)

Development of an ICRH antenna system at W7-X for plasma heating and wall conditioning

B. Schweer[a], J. Ongena[a], V. Borsuk[d], D. Birus[d], S. Bozhenkov[d], D. Castaño Bardawil[b], F. Durodié[a], D. Hartmann[d], K. P. Hollfeld[c], P. Kallmeyer[d], A. Krivska[a], F. Louche[a], A. Messiaen[a], O. Neubauer[b], G. Offermanns[c], G. Satheeswaran[b], M. Van Schoor[a], M. Vervier[a], R. Wolf[d]
and the W7-X team[d]

[a] LPP-ERM/KMS, Trilateral Euregio Cluster (TEC), 1000 Brussels, Belgium
[b] Forschungszentrum Jülich GmbH, IEK-4, Trilateral Euregio Cluster (TEC), 52425 Jülich, Germany
[c] Forschungszentrum Jülich GmbH, ZEA-1, 52425 Jülich, Germany
[d] Max Planck Institut für Plasmaphysik, 17491 Greifswald, Germany

Abstract

An ICRH antenna system is under construction to be ready for use in the operational phase 1.2 of W7-X A two strap antenna, with a surface adapted to the 3D shape of the LCFS of the standard magnetic configuration (m/n=5/5), will be installed in the equatorial plane on the low field side of W7-X. The antenna system is optimised for plasma heating and wall conditioning in presence of the magnetic field in the frequency range 25 - 38 MHz. Each strap is short-circuited on one end, is pre-matched using a tunable capacitor on the other end with connection to the RF power source about halfway in the poloidal direction. To allow optimal coupling to different magnetic configurations in W7-X the antenna can be moved radially over a distance of 350 mm. The cooling circuits in the antenna head are designed to sustain cw W7-X plasma operation in a retracted position and 2 MW ICRH pulses with max. 10 s duration every 300 s close to the LCFS.

Keywords: W7-X, ICRH antenna, heating, fast particle generation, wall conditioning

1. Introduction

Plasma in the optimised stellarator W7-X is mainly produced by electron-cyclotron resonance heating (ECRH). Additional heating power is coupled to the plasma by neutral beam injection (NBI) and ion cyclotron resonance heating (ICRH). Figure 1 shows the design of the main components of an ICRH system designed for W7-X. The ICRH antenna system is intended to:

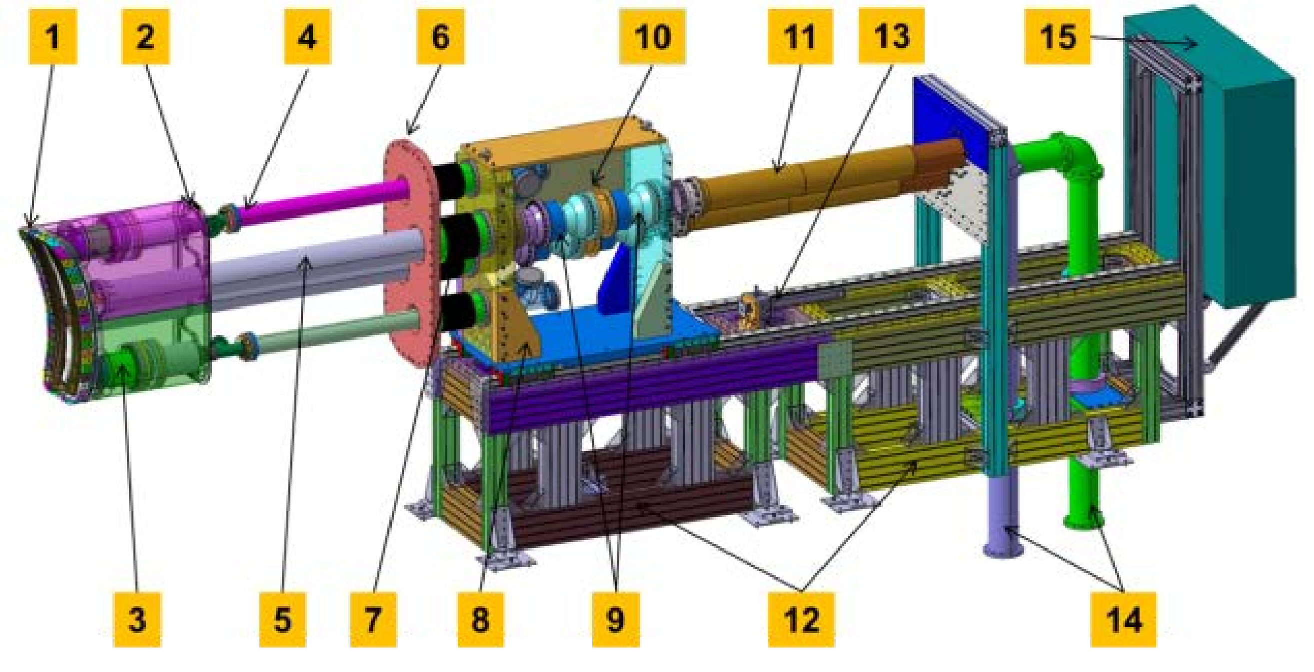

Fig. 1: Design of the ICRH antenna system at W7-X (1:antenna head with carbon protection files, 2:short circuit to AEE31 duct, 3:tunable capacitor, 4:supply tubes for water cooling circuits and diagnostics, 5:coaxial RF transmission line, 6:cryostat flange, 7:bellow, 8:movable antenna support, 9:RF feedthroughs, 10:control volume, 11:line stretcher, 12:support tables, 13:radial motion motor, 14:RF lines interface with dc break, 15:electrical cabinet with WinCC panel)

a) Provide plasma heating with coupled power up to 2.0 MW depending on the actual coupling for 10 s every 300 s from two generators in the frequency range 25 to 38 MHz.
b) Generate high energy ion tails (100-200 keV), to study fast particle confinement
c) Provide wall conditioning in presence of a constant magnetic field with continuous low power ICRH operation.

In the final stage of implementation the ICRH antenna will be fed by two radio-frequency (RF) generators, located together with the matching system outside the torus hall. The RF power is transported to the antenna, located in the AEE31 port at the low field side of W7-X, using two coaxial transmission lines. Figure 1 shows the main components of the ICRH system, planned for installation in W7-X in January 2018. Operation of the antenna system must be compatible with long pulse operation (30 min.) for all foreseen magnetic field configurations in W7-X. To reduce the voltage in the lines, the antenna is pre-matched by tunable capacitors. Coupling is optimised by a carefully controlled setting of the antenna position close to the LCFS. The movement can be performed within temperature limits at the wall and straps of the antenna head. Between RF pulses the antenna is retracted into the port duct to minimise the heat load from the plasma.

2. Mechanical design

For optimal coupling of RF power the antenna surface should have the same shape as the LCFS of the plasma and this is the case for the so-called standard magnetic field configuration in W7-X (m/n=5/5). The straps are recessed inside the antenna box by 10 mm to avoid short circuiting of the straps to antenna box or plasma via the magnetic field lines.

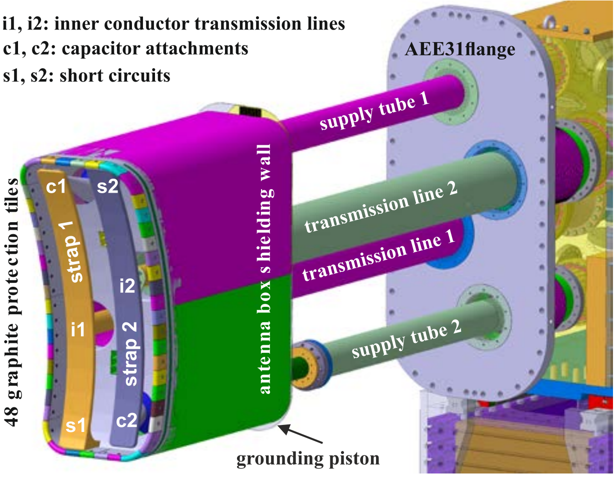

Fig. 2: ICRH components in the ultra-high vacuum of the W7-X inner vessel

The radial position and poloidal and toroidal structure of the LCFS is different for other magnetic configurations. When not in use, the antenna is retracted into the AEE31 port duct. During operations it can be moved radially over 350 mm with a speed of 3 mm/s to the desired position near the LCFS of the magnetic configuration in use.

The antenna head, moving in the AEE31 duct, consists of a stainless steel box (outer dimensions: 924 mm height, 378 mm width), comprising two straps (866 mm height, 90 mm width, 15 mm depth); each strap is short-circuited at one end (s1, s2) and connected to a tunable capacitor (2-200 pF) at the other end (c1, c2). About halfway in poloidal direction the straps are connected to the inner conductor of the coaxial RF transmission lines (i1, i2) [1]. All antenna components shown in figure 2, located in ultra-high vacuum are radially movable.

The plasma facing surfaces of the antenna box are shielded with graphite tiles and are also shaped parallel to the LCFS of the standard magnetic configuration within ±0.3 mm accuracy. Heat transfer between graphite and steel is improved by a 0.2 mm thick GRAFOIL® sheet.

The heat load from the plasma is removed by cooling water channels underneath the tiles and near the rear side of the box as can be seen in figure 3.

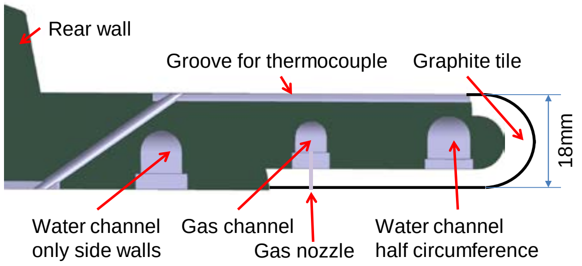

Fig. 3:Cross-section of side wall of the antenna head with water pipes and channels for gas puffing.

3. Thermal properties of antenna components

The temperature distribution in the cross-section of the graphite and stainless steel wall parts of the antenna head are modelled with ANSYS assuming a conductive heat exposure of 1.0 MW/m^2 at the tip of the graphite tiles and an exponential power decay length of 10 mm.

The result, assuming a heat transfer coefficient in the graphite foil of 1 kW/m^{2}K, is presented in figure 4. At the graphite tile the surface temperature reaches up to 940^{o}C with a large temperature drop of about 550 K within the graphite foil. This has been confirmed experimentally with a wall mock-up irradiated with the electron beam device JUDITH-1 [2]. Equilibrium surface temperatures of about 1500^{o}C were obtained with repetitive heat load pulses of 2 MW/m^2 without any damage to the tiles.

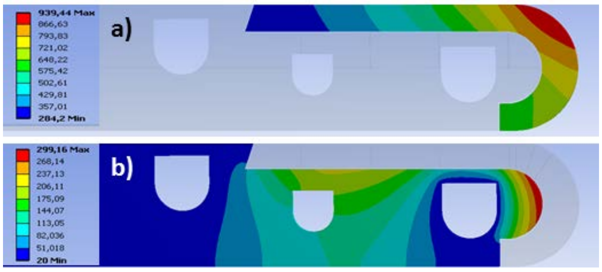

Fig. 4: ANSYS modelling of the temperature distribution in the vertical antenna wall with a conductive heat transfer coefficient of 1000 Wm^{-2}K^{-1}for graphite (a) and stainless steel (b)

The water cooled straps are made of low cobalt stainless steel (SS1.4429, Co≤500ppm). The surface temperature is mainly influenced by cw plasma radiation, which in worst case for detached plasma can be 100 kW/m^2.

During antenna operation the straps receive an additional heat load from the RF within the skin depth

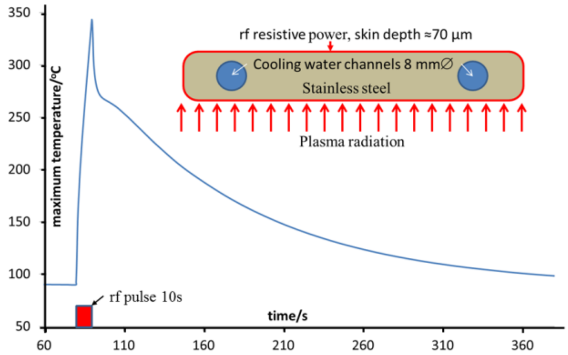

Fig 5: Temporal evolution of the maximum strap temperature assuming 100 kW/m^2 continuous radiation from the plasma and 100 kW RF resistive power during 10 s

For such conditions the temperature distribution in the strap cross-section was calculated by ANSYS modelling assuming a maximum cw radiation to the plasma facing side of the strap and a 100 kW resistive power pulse converted into heat for 10 s. This last value depends strongly on the relative phasing of the two straps and is not homogeneously distributed around the strap circumference [3]. In 0-π phasing the resistive power can reach 75 kW. A large rise in the surface temperature is induced by the RF power, as can be seen in figure 5. The initial temperature ($t \leq 80$ s) is determined by the plasma radiation. The highest temperature of 340°C is reached after a 10 s pulse, followed by a strong decay over 4 s, and induced by a volume effect. In the presence of the cw plasma radiation the surface temperature needs about 300 s to return to the initial value.

The temperature distribution in the strap cross-section together with its temporal evolution from the combined effect of a cw heat load from plasma radiation and a single RF pulse is presented in figures 6a to 6d.

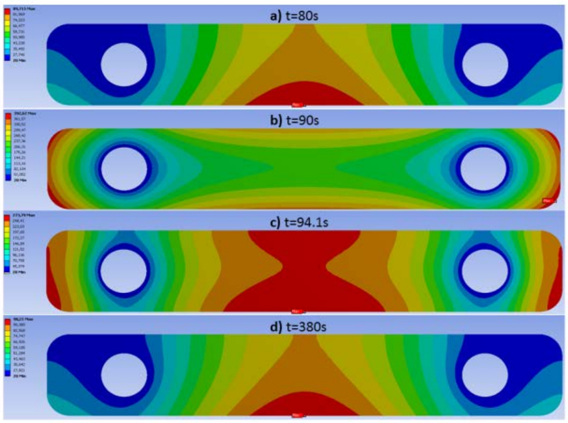

Fig. 6: Spatial distribution of the temperature in the cross-section of one stainless steel strap with 100 kW/m^2 continuous radiation from the plasma and additional 100 kW resistive heating of the surface by RF power for 10 s. ***a)*** *before and* ***b)*** *after the RF pulse,* ***c)*** *after 4.1 s and* ***d)*** *290 s relaxation time*

4. Main design features

The capacitors are mounted tiltable to exclude mechanical stresses on its ceramic component caused by the thermal expansion of the straps. The antenna box must be discharged to the duct wall. In a distance of 590 mm behind the rear side of the antenna head a plate is fixed at the transmission tubes with good electrical contact, which nearly fits into the antenna duct cross section (no.2, Fig.1). Air powered pistons are pressing electrical contacts to the duct allowing to ground the antenna box even during movement. The volume between the rear plate and antenna head is closed by thin stainless steel sheets to reduce the influence of ECRH radiation on electrical connections (Figure 2).

The RF transmission lines in UHV also mechanically support the antenna box and are connected with a radially movable carrier (no. 8 in fig. 1) outside the cryostat. UHV conditions are maintained by edge welded bellows, which can compensate a movement of 350 mm (no.7 in fig. 1). Two additional tubes containing diagnostics cables, water circuits, pressurized air tubes, waveguides (no. 4 in fig. 1) and capacitor tuning rods are connected to the rear side of the capacitors. These volumes (each 15 ℓ) are evacuated down to10^{-3} mbar and then filled with 50 mbar neon. This pressure is controlled and the use of Ne allows an easy identification of a vacuum leak. Inside the carrier housing two air-vacuum feedthroughs connected in series are installed in each coaxial transmission line (no. 9 in fig. 1) to minimise the risk of unintentional venting of the plasma chamber. For safety reasons the control volumes (7.4 ℓ) between two feedthroughs are also filled with neon to a pressure of 1.1 bar to avoid RF breakthroughs and to identify a vacuum leak.

All components in the antenna head are water cooled at pressures up to 15 bar sufficient also for wall conditioning at 150°C. Four water circuits in the antenna head and two in the straps are designed to allow operation of the ICRH antenna system during long plasma discharges with full ICRH power every 300 s. The total water flow for all circuits is 5.4 m^3/h. Unfortunately, for material and design reasons the capacitors need a separate cooling circuit to limit the temperature below 100°C and the water pressure below 3 bar during wall conditioning. The temperature difference of 50 K between the antenna head and the capacitor creates a heat flow of about 250 W per unit, which must be removed by the separate cooling system. The supply temperature during wall conditioning should be as close as possible to 100°C to minimise the adsorption of released gases from the inner vessel. A water flow of 0.5 m^3/h meets this requirement and is also sufficient to remove about the additional 60 kJ heat load, produced in both capacitors during the RF pulse. The RF power from the two generators is passing DC breaks and then fed into the antenna system through two line stretchers (no. 11 in fig. 1) to compensate for the radial movement of the antenna carrier. The coupling of RF power is strongly dependent on the shape of the edge density. Gas puffing (H_2 or D_2) into the scape-off layer is foreseen to improve the RF coupling conditions using gas pipes with 1 mm diameter holes at both sides of the antenna head wall and connected with 6 mm diameter gas supply tubes (fig. 3). Two Piezo valves mounted at the rear side of the antenna box can deliver gas pulses equal to or longer than 10 ms. The gas flow can be adjusted by a preset pressure up to 10 bars.

5. Antenna diagnostic

At 8 positions in the graphite tiles along the circumference of the antenna head wall the temperature is measured by type K thermocouples. An additional four type K thermocouples are mounted in the center and capacitor side of the straps (Figure 7a).

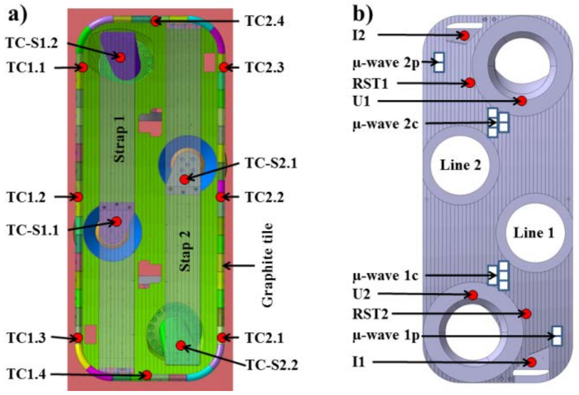

Fig. 7: Location of various diagnostics at the antenna head a) front view with thermocouples, b) rear view with RF current, RF voltage probes and µ-wave horns for profile and correlation measurements. (See Table 1 for the signal names)

Furthermore, resistive thermal sensors (RTS) Pt100 are mounted at the capacitor housings and at the rear side of the antenna box to monitor the heat load distribution. Each line is foreseen with RF current and voltage probes (figure 7b). Microwave reflectometers are foreseen to measure the electron density profile in front of the ICRH antenna head. One pair of horn antennas is mounted in the upper, and one in the lower part of the rear wall of the antenna head (figure 7b). Near the equatorial plane two groups of each 5 horn antennas, are proposed for poloidal correlation spectrometry in the operational phase OP2 of W7-X to measure turbulence characteristics of the plasma.

	Parameter	Signal name	Parameter
TC1.1	temperature Type K thermocouples	TC2.1	temperature Type K thermocouples
TC1.2		TC2.2	
TC1.3		TC2.3	
TC1.4		TC2.4	
TC-S1.1		TC-S2.1	
TC-S1.2		TC-S2.2	
U1	RF voltage	U2	RF voltage
I1	RF current strap-wall	I2	RF-current strap-wall
I1-C	RF current capacitor 1	I2-C	RF current capacitor 2
µw-1p	electron density profiles	µw-2p	electron density profiles
µw-1c	correlation reflectormetry	µw-2c	correlation reflectormetry
RTS1	temperature Pt100	RTS2	temperature Pt100
RST1-C		RST2-C	

Table 1: List of foreseen diagnostic signals (diagnostics for signals in shadowed cells are not shown in fig. 7)

6. Antenna SPS control

The complete ICRH system, outside and inside the torus hall, is controlled by a PLC (Siemens S410H) based on PCS7 programming. It serves as local control and interacts with the W7-X central control. Inside the torus hall a WinCC touch panel at the cabinet (no. 15 in fig. 1) allows local operation during maintenance. Other panels are at located at the RF generators and in the main diagnostic room.

The antenna unit in the torus hall is electrically insulated and only grounded at the cryostat port. Therefore also all temperature signals (sample rate of 25 Hz) are decoupled by insulation amplifiers. The RF current and voltage signals are guided through coaxial cables to a conversion box, which delivers the amplitude and phase relation. All valves, flow meters and electrical motors are electrically decoupled as well.

The antenna head is completely retracted from the plasma chamber when there is no ICRH operation. However, all water cooling circuits should be actively controlled during plasma operation, independent of the operation of the ICRH system, and are therefore part of the central machine safety system.

In case of vacuum conditioning the cooling water is heated up to 150°C. The local PLC has only to control the temperature (≤100°C) and pressure (≤3 bar) of the capacitor water circuits and will continuously deliver a status signal to the central control.

The pressure in the intermediate vacuum volumes has also to be continuously monitored. Error messages are sent as soon as the pressure of the neon gas deviates from preset ranges. The temporal evolution of the pressure allows the identification of leakages to air or to UHV.

For ICRH operation the capacitors are pre-adjusted with DC server motors by the operator. At a given trigger from the W7-X central control system, the antenna system, driven by an AC motor, will be moved with 3 mm/s to a given position close to the LCFS. The ICRH pulse follows and the temperatures at the graphite tiles are the main parameter for the feedback control of the linear motion AC motor. If the temperature gradient exceeds a given threshold the antenna is retracted gradually. A sudden loss of RF coupling identified by a change in the reflected power might be recovered by a gas puff (H_2 or D_2), which is generated by activation of two Piezo valves located at the rear side of the antenna head.

After the ICRH pulse (≤10 s) the antenna is moving back to the parking position in the duct. A successive pulse is only possible if the temperatures of the components are below given thresholds.

7. References

[1] J.Ongena et al., "Physics and applications of ICRH on W7-X", 26th IAEA Fusion Energy Conference, Kyoto, 17-22 Oct, Paper EXD/5

[2] R. Duwe, W. Kühnlein, H. Münstermann 1994, Fusion Technology 355–358

[3] Lamalle P. et al., LPP Report 129 (2007)

This work has been carried out within the framework of the EUROfusion Consortium a nd has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.