The 140 GHz, 10 MW, CW ECRH Plant for W7-X: A Training Field for ITER

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Abstract. Both, the W7-X Stellarator, which is under construction at IPP-Greifswald, and the ITER Tokamak, which will be built at Cadarache, France, will be equipped with a strong ECR-Heating and current drive system. Both systems are similar in frequency and have cw-capability (140 GHz, 10 MW, cw for W7-X and 170 GHz, 24 MW, 1000 s for ITER). The commissioning of the ECRH plant for W7-X is well under way, the status of the project and first integrated full power, cw test results from two modules are reported. As the technological demands for ECRH have many similarities in both, the W7-X and ITER devices, results and experience from the W7-X ECRH may provide valuable input for the ITER plant. The installation at W7-X was already used successfully as a test bed for ITER ECRH- components under high power conditions.

1. Introduction

The physics goals for the W7-X Stellarator determine the main machine parameters as well as a consistent set of heating systems, diagnostics, data acquisition and machine control. W7-X (major radius 5.5 m, minor radius 0.55 m) is the next step in the Stellarator approach towards magnetic fusion power plants. In contrast to Tokamaks, Stellarators have inherent steady state operation capability, because the confining magnetic field is generated by external coils only. The scientific objectives for W7-X can be formulated as follows:

1. Demonstration of quasi steady state operation at reactor relevant parameters, with $T_e = 2$-10 keV, $T_i = 2$-5 keV and $n_e = 0.1 - 3\ 10^{20}\ m^{-3}$
2. Demonstration of good plasma confinement
3. Demonstration of stable plasma equilibrium at a reactor relevant plasma ß of about 5 %
4. Investigation and development of a divertor to control plasma density, energy and impurities.

W7-X is equipped with a superconducting coil system, a continuously operating heating system and an actively pumped divertor for stationary particle and energy control. In contrast to ITER, W7-X does not aim at DT-operation and provisions for remote handling in a radioactive environment are not foreseen. ECRH is the main heating system for steady state operation. The high-ß criterion will be addressed in pulsed experiments (< 10 s) at reduced magnetic field in a later state of the machine operation, where Neutral Beam Injection Heating will be available with 20 MW for 10 s.
An ECR-heating power of 10 MW is required to achieve the envisaged plasma parameters [1] at the nominal magnetic field of 2.5 T. The standard heating and current drive scenario is X2-mode with low field side launch (LFS). High-density operation above the X2 cut-off density

at 1.2 10^{20} m^{-3} is accessible with O2-mode (< 2.5 10^{20} m^{-3}) [2] and at even higher densities with O-X-B mode conversion heating [3]. Theoretical investigations show [4], that X3-mode heating (B_{res}= 1.66 T, n_e < 1.6 10^{20} m^{-3}) is a promising scenario for operation at reduced magnetic field, which would extend the operation-flexibility further. As W7-X has no OH-transformer for inductive current drive, EC-current drive is a valuable tool to modify the internal current density distribution and to counteract residual bootstrap currents. The physics demands for both, W7-X and ITER request a versatile and flexible 'day one' ECRH-system with high reliability. The following table compares some basic features of both systems:

TABLE I. ECRH FOR W7-X AND ITER, MAIN PARAMETERS

	W7-X	**ITER**
Power (MW)	10	24
Power per Gyrotron (MW)	1	1 (2)
Frequency (GHz)	140	170
Operation Mode (standard)	2nd Harm. (2.5 T) cw (1800 s)	1st Harm. (5.6 T) cw (1000 s)
Transmission	optical	waveguide
Launcher	Front steering	Front steering/ Remote steering
Physics demands	Bulk Heating and Current Drive	Bulk Heating and Current drive
	q-profile shaping	q-profile shaping
		MHD-control
	Net-current suppression	Net-current enhancement

2. General design: The 'modular concept'

The total ECRH power is generated by 10 gyrotrons operating at 140 GHz with 1 MW output power in cw-mode each. To achieve maximum reliability and availability, we have chosen a modular design, which allows commissioning and operation of each gyrotron and the required subsystems independently from all others. Repair or maintenance of one module is possible without affecting the operation of all other gyrotrons. This design also minimizes the costs because series production of identical modules is possible. It is evident from this concept, that the demonstration of cw-operation at full power with one module gives high confidence in the full system capability and is therefore a major milestone in the ECRH-project (achieved in 2005).

An optical transmission system was developed for W7-X, which, after careful analysis, turned out to be the most simple, reliable and cost effective solution [5]. The transmission of the rf-power to the torus (typically 60 m) is performed by two open **m**ulti-**b**eam **w**ave**g**uide (MBWG) mirror lines, each of them combining and handling 5 (+2) individual rf-beams (7 MW). The **s**ingle **b**eam **w**ave**g**uide (SBWG) sections near the gyrotrons and the torus ports have a strictly modular design also with identical components. The power handling capability has inherently a large safety margin (factor of 2-3) due to the low power density on the mirror surfaces. We thus have the option to replace the 1 MW gyrotrons by more powerful ones in a later state, if such Gyrotrons become available. It is worth noting, that the W7-X transmission system would satisfy the ECRH (24 MW) power capability demands for ITER without modification. A sketch of the ECRH-plant and the integration of the various components in the ECRH-building are shown in Fig.1 (left), the modular structure is seen from the photographs in Fig.1 (right). An underground concrete duct houses the individual components of the transmission system, the concrete walls are an efficient absorber of stray radiation from the open lines thus satisfying the safety-requirements on microwave shielding. All mirrors in the beam duct are remotely controlled.

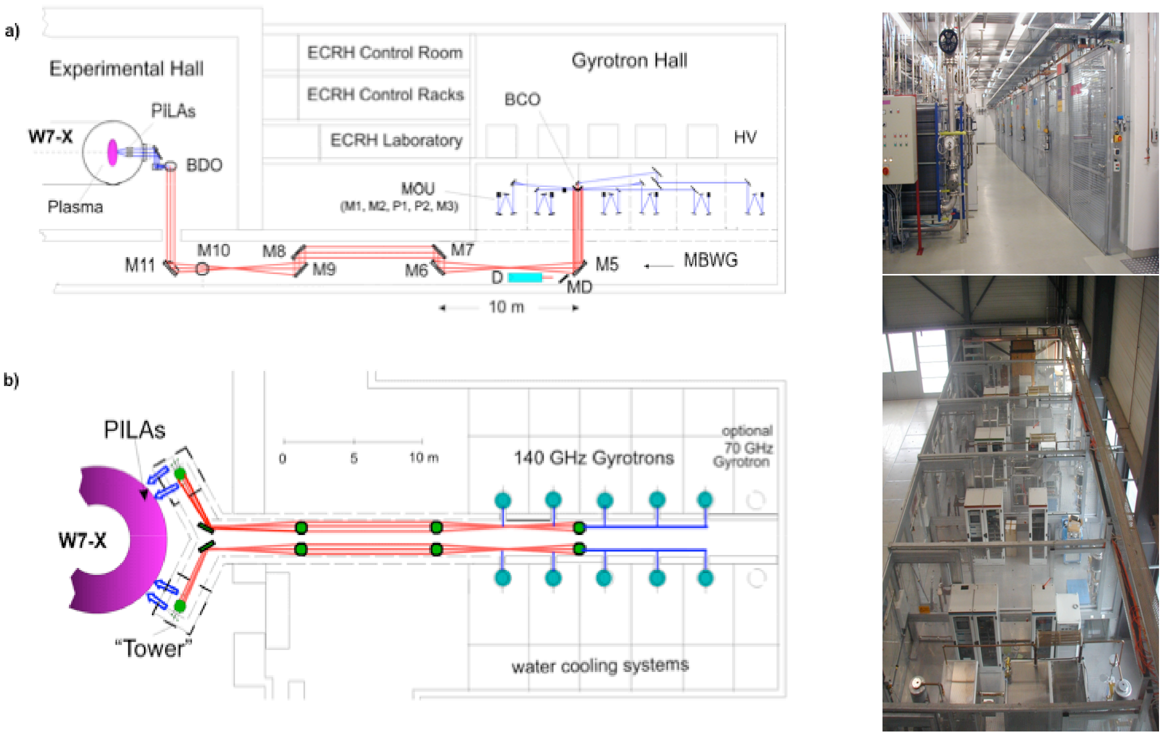

FIG. 1. The ECRH-plant for W7-X: Left: sketch of the gyrotron and transmission line arrangement in the ECRH-building, cross section (a) and top view (b). Right: Modular arrangement of Gyrotron and cooling units (top). HV-installation at ground-floor (bottom).

3. The W7-X Gyrotron

The development of cw-gyrotrons with an output power in the megawatt range for fusion application was and still is subject of a worldwide R&D effort, which is mainly driven by the needs of the two large fusion devices W7-X and ITER. The development of the 'W7-X gyrotron' started in 1998 in Europe with Thales Electron Devices (TED) and in USA with CPI as industrial partners and was successfully completed in 2002. The design approach for both development lines is based on 'diode-type' gyrotrons (no control anode) to simplify the design and single-stage collector depression to enhance the efficiency. Detailed results from the TED R&D- and series gyrotrons are reported in [6,7], results from the R&D at CPI are reported in [8], respectively. A maximum output-power of 0.96 MW with an efficiency of 44 % was measured in 3 min operation (TED). Slightly more conservative parameters were chosen for the 30 min operation and a directed beam power of about 0.9 MW (CPI) and 0.92 MW (TED SNo1) were obtained. Power modulation up to 20 kHz by modulating the body voltage only was demonstrated.

FIG. 2. The TED SNo.1-Gyrotron at IPP.

4. Transmission line and in-vessel components

The general arrangement of the transmission system is sketched in Fig. 1(left). The gyrotrons are installed behind the concrete walls of the underground beam duct as seen in Fig.2, the microwave beams are transmitted through holes in the duct walls. The beam conditioning for each gyrotron is provided by a SBWG module consisting of five single-beam mirrors. The SBWG module is instrumented with additional components such as short-pulse calorimeter, rf-diagnostics for in-situ beam monitoring, an rf-bolometer, rf-shielding elements and switch mirrors as seen from Fig.3 (top). The **b**eam **c**ombining **o**ptics (BCO) module is also seen in the background. Two SBWG-mirrors (M1 and M2) match the gyrotron output to a Gaussian beam with the correct beam parameters. The next two mirrors (P1 and P2) are corrugated with a sinusoidal corrugation [9] to set the polarization for the different heating scenarios and current drive. A fifth mirror (M3) directs the beam to a plane mirror array (BCO) at the input plane of the MBWG. The mirror SC allows switching of the beam towards a short pulse calorimeter (C) for power calibration. The calorimeter operates in repetitive mode at a pulse length ranging from 0.5 ms to 0.5 s. The MBWG is designed to transmit up to seven beams (five 140 GHz beams, one 70 GHz beam plus one spare channel). Four focusing and three additional plane mirrors are required to fit the transmission lines into the building (see Fig. 1 (left)). A section of the two symmetrically arranged MBWG's is shown in Fig. 3 (bottom) together with the cw- loads.

FIG. 3. The W7-X quasi-optical transmission system. Top: Single beam section with BMO (M1,M2), short-pulse calorimeter (C), polarizers (P1,P2), microwave absorbers (AB1) and feeder mirror (M3) mounted on a common base frame. The beam path is indicated. Bottom: Section of the Multi-Beam-Waveguide, both cw-loads (L) are seen in the background.

The two rf-beam bundles enter the main torus hall through the floor, thus avoiding complicated labyrinth beam paths, which would be required for neutron shielding if the beams would penetrate the hall through the 1.8 m thick concrete sidewalls. Two towers house the mirror array (beam distribution optics, same as the BCO-module) at the output plane of the MBWGs, which separates the beams and directs them via two mirrors towards the plug-in launchers. The spare channel of the MBWGs is used to switch one beam on each side from a standard LFS launcher to a high field side launcher in the N-ports. No detailed design exists yet for the N-port launcher. The remote steering concept may be an attractive option, because of the very limited port-space.

Note the functional similarity with the ITER-system, where all transmission lines have switches from the equatorial port (heating and CD) to the upper port, which is dedicated to NTM-stabilisation. The length of the MBWGs is 45 m, the total length of the transmission lines is 57 to 65 m depending on the location of the gyrotron. The total transmission efficiency of a full scale prototype system (17 mirrors) was checked by calorimetric methods and yielded 90±2 %, which is in good agreement with the theoretical value.

The 12 RF-beams (10 plus two spare) will be launched through 4 large equatorial ports (type A and E) for the LFS-launch scenarios. Three beam-lines are stacked and incorporated into one plug-in launcher (PILA) as shown in Fig. 4 (left). Each beam is transmitted through a synthetic diamond vacuum window towards a fixed focusing mirror and a bi-axially movable, plane steering mirror at the launcher front end. Water-cooled tubular structures are screening the beams and serve as a rigid mechanical support for the front mirrors. Specially designed apertures inside the beam tubes reduce the level of reflected power. The movable mirrors

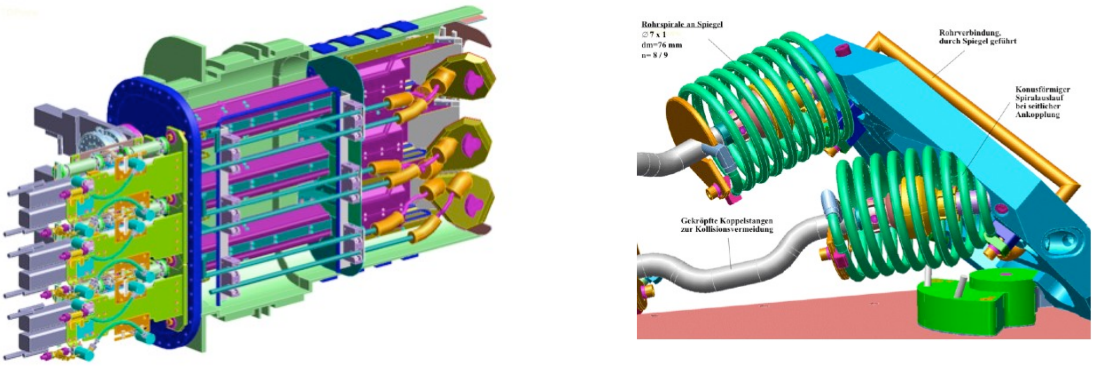

FIG. 4: Left: Front steering plug-in launcher. Right: Detail of the movable front mirror with driving rods and cooling spirals.

have a steering range of ±25° in poloidal and between ±15° and ∓35° in toroidal direction, respectively. The cooling water of the front mirror is fed through two push-pull rods, which are used for the mirror positioning. The joints of the rods are bridged by tube spirals as shown in Fig 4 (right). Copper half-shells and the surrounding tube spirals screen the joints against microwave and plasma radiation. Worst-case assumptions for the design are a microwave radiation of about 500 kW/m^2 in the port duct and a plasma radiation of 100 kW/m^2 in the front mirror area. A launcher mock-up was build, which incorporates all critical elements in original size. In a mechanical test with 10000 full scan cycles a positioning accuracy of 0.05 deg was measured. The motor drive was also successfully tested in a magnetic field of up to 40 mT, which is expected at the final motor position near the stellarator. The most critical elements are the stainless steel tube spirals, which have to withstand both a bending angle of up to 45° and a torsion of 10°. After the successful tests of critical subcomponents, the parts were integrated into the mock-up launcher, which is presently being tested in a special **Mi**crowave **St**ray **Ra**diation **L**oading (MISTRAL) test facility shown in Fig.5. Critical in-vessel components for W7-X can be tested under vacuum-conditions and in presence of an rf stray-radiation background. The high stray radiation level, which is expected in the W7-X vacuum vessel (about 200 kW/m^{-2} in the vicinity of the ECRH-launchers) could thermally overload insufficiently cooled in-vessel components (first wall, diagnostics, divertor, etc.) and generate sparks in wavelength resonant structures. The MISTRAL facility is presently powered with an average, cw-power of 30 kW at 140 GHz, which generates the expected background radiation of W7-X. The chamber with a diameter of 1.5 m and a length of 2.2 m has Al-walls with high reflectivity and a rough inner surface, which, in combination with a special feeder antenna system, generates a

FIG. 5: The MISTRAL-facility. The large A-port is seen at the front side.

homogenous and isotropic background radiation in the central region of the vessel. A set of standard vacuum ports, which are used in the W7-X vacuum vessel, and one of the large, elongated A-ports give access to the vessel. The A-port houses the full size ECRH plug-in launcher (1.8 m long) for integrated tests.

5. Integrated high power, cw tests

Successful full performance tests of gyrotrons from both manufacturers, CPI and TED were performed in 2005. The test arrangement was similar for both Gyrotrons: The microwave beams were transmitted through 7 single beam mirrors as described in Sec. 4 and coupled to the calorimetric cw-load via a special mirror (MD, see Fig. 3, bottom).

It is worth noting, that all peripheral systems at IPP such as the main power supply, central cooling system, body-modulator, transmission line components, rf-diagnostics, as well as the central control and data-acquisition system went through this integrated qualification process. Typical time traces of the output-power and the Gyrotron pressure (GIP-current) for an experimental sequence of one short (5 min) and one longer pulse (30 min) are shown in Fig. 6. The slow rise and fall times of the rf-power trace is determined by the characteristic time constant of the cw-calorimeter. A steady increase of the Gyrotron pressure, although at very low level of a few μA, indicates, that the Gyrotron has not yet reached steady state after 30 min, although all other parameters became stationary.

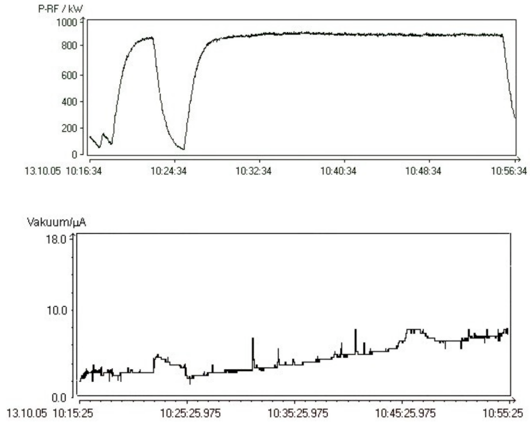

FIG. 6. TED SNo.1: RF-power (top) and gyrotron vacuum (GIP-current)(bottom) as a function of time (h.min.sec).

Note, that due to the inherent mode filtering capability of a beam waveguide only the Gaussian mode content of the gyrotron beam reaches the cw-load. The total transmission losses after seven mirrors were estimated in the range 50-70 kW. As the beam parameters for the CPI-gyrotron were not known with the required accuracy, slightly higher losses (70 kW) resulting from an imperfect Beam-Matching-Optics unit had to be accepted as compared to the TED-Gyrotron (50 kW). The measured power in the calorimetric load was 870 (TED) and 830 kW (CPI), respectively. During high-power tests all mirrors performed well. In particular, no arcing was seen on the corrugated surfaces of the polarizers, provided that they were clean. The polarizers are the most loaded and probably the most critical elements.

Small side lobes of the rf-beam were hitting the beam duct concrete wall or weakly cooled elements like the first mirror-support and additional water cooled absorbing targets had to be installed at the measured hot spots to avoid overheating. It is expected, that some fraction of the lost power will be recovered by an improved BMO, which would increase the useful power in the Gaussian mode. More important, however, is the reduction of the power in the beam side-lobes, because even a small fraction of directed power (some kW), which does not hit the water cooled transmission mirrors, may create hot spots and damage of weakly cooled surfaces in cw-operation. The more or less isotropic deposition of the small fraction of stray radiation is easily handled by the concrete walls and is of minor concern.

The CPI-gyrotron opened a vacuum leak after having passed the acceptance test and was returned to the manufacturer for repair. The TED Gyrotron S No. 1 was mothballed after the acceptance tests. With the encouraging results from the integrated tests of two modules, series production and commissioning of the major system components were released. Both TED

R&D gyrotrons are routinely used for component tests. At present, 4 out of the 10 units of the ECRH-plant are operational, the others are in different states of completion. Although the TED gyrotron S.No. 2 failed to meet the required output power during the tests at FZK and will be returned to the manufacturer, series production is ahead of the limited test-and commissioning capability at FZK and IPP. The TED gyrotron S.No.3 is presently being prepared for full performance tests at IPP, S.No.4 is close to completion in the factory.

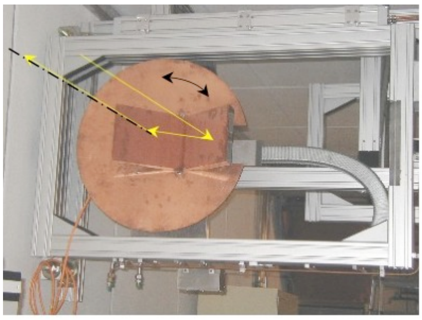

FIG.7: Retro-reflector in the beam duct.

The high-power, full performance, cw tests reported here were restricted to the SBWG-section of the transmission line, because the optical elements in the torus hall, which are a necessary prerequisite, can be installed and tested only in a late phase of the W7-X-torus assembly. For tests of the full distance transmission including the MBWG-section, a special optical arrangement with retro-reflectors mounted in the first image plane of the MBWG (i.e. at half distance of the MBWG (see Fig. 1) is thus being prepared as an intermediate step. As seen from Fig.7, the retro-reflector is mounted on a turntable to reflect either one of the six beams, which are propagating forward in an outer channel of the MBWG, backward via the central channel. The direction of the incident and reflected beam, the axis of symmetry (dashed dotted line) and the rotation direction is indicated. An additional movable mirror near the entrance plane of the MBWG focuses the beam finally (via mirror MD) into the cw load.

Although the TED gyrotrons are optimized for single frequency operation at 140 GHz, we have investigated operation at a second frequency. The gyrotron window has a resonant thickness of 4 $\lambda/2$ and is thus resonant also at 105 GHz. Two cavity modes exist in the vicinity of 105 GHz, the $TE_{21,6}$ and the $TE_{22,6}$ modes with frequencies at 103.8 and 106.3 GHz, respectively. Both frequencies, although not perfectly matched, are compatible with the window transmission characteristics (reflectivity below -20 dB within $\pm$ 1 GHz at 140 GHz). We have demonstrated very recently, that both modes can be excited. First experiments focused on the $TE_{21,6}$ mode, because the gyrotron output beam is almost perfectly centered on the window and has a slightly higher quality as compared to the other mode. In preliminary experiments we have obtained up to 530 kW in diode operation (no depression) with an efficiency of 21 %, which is slightly higher than the theoretically predicted value of 17 %. The collector loading is about 1.9 MW in this case, which is incompatible with the loading limit of 1.3 MW. A very conservative operation point was found with reduced collector loading of 1.1 MW (with depression) and an output power of 410 kW. The corresponding efficiency is 27 %. The pulse length was extended to 10 s and no limitations could be found so far. It is worth noting, that the rf-beam was transmitted through the 7-mirror system with a minor realignment only, using the beam-matching optic and the polarizers, which are designed for 140 GHz. Although there is still margin to increase the rf-power, the results obtained so far are already attractive. A new W7-X operation regime at B_{res}= 1.86 T with $n_e <$ 0.7 10^{20} m^{-3} (X2) becomes accessible, which may be helpful especially in the early exploration phase of W7-X and for physics investigations with B as the leading parameter.

6. The ECRH-plant: A test bed for component tests

The ECRH-system served already as a high power test bed for ITER ECRH-components, which were developed at different laboratories. The open transmission system, which allows an easy implementation of different test arrangements in the existing transmission system, turned out to be the key-feature for fast and efficient testprograms: The mock-up version of a remote steering launcher, which is an option for the ITER upper launcher, was tested with an rf-power up to 700 kW and pulse lengths of 10 seconds at IPP-Greifswald [10]. No arcing was observed within this range of power and pulse-length, in spite of the fact, that the experiments were performed under ambient atmospheric conditions. Short-pulse radiation pattern measurements with thermographic recording showed high beam quality and have confirmed the predicted steering range of $-12° < \varphi < 12°$.

High power, short pulse tests of a mock-up version of a 2 MW calorimetric load were also successfully performed recently, details are presented in [11].

7. Summary and conclusions

The ECRH-system for W7-X is the most ambitious and largest cw-plant presently under construction, its relevance for ITER is obvious. The successful full performance cw-tests of two out of 10 ECRH-modules have proven, that the ECRH-system is based on a viable and robust design. The R&D phase for the Gyrotrons and the transmission line was terminated and series production, installation and commissioning is in progress. The modular concept proved to be essential for the project realization. MW-class cw-gyrotrons at the required frequency are now commercially available from two industrial manufacturers. The quasi-optical multi-beam waveguide system offers favorable transmission characteristics close to the theoretical predictions and the most loaded components showed an excellent performance under full power, cw conditions. The test results and the operational experience may provide valuable input for the ITER-ECRH system, because the physics demands and the main system parameters are comparable. The ITER-system must, however, satisfy additional requirements such as operation and maintenance in a radioactive environment.

References

[1] V. Erckmann, H.J. Hartfuß, M. Kick, H. Renner, et al.: Proc. 17th IEEE/NPSS Symposium on Fusion Engineering, San Diego, USA (1997). Ed. IEEE, Piscataway, NJ 1998, 40 - 48

[2] M. Rome', V. Erckmann, U. Gasparino, N. Karulin, Plasma Phys. Control. Fusion 40 (1998) 511-530

[3] H. P. Laqua, V. Erckmann, H.J. Hartfuß, H. Laqua, W7-AS Team, and ECRH Group, Phys. Rev. Lett. 78, 3467 (1997)

[4] V. Erckmann, P. Brand, H. Braune, G. Dammertz, et al., to be published in Fusion Science and Technology

[5] W. Kasparek, P. Brand, H. Braune, G. Dammertz, et al., Fusion Engineering and Design 74 (2005) 243-248

[6] G. Dammertz, S. Alberti, A. Arnold, E. Borie, et al., IEEE Trans. Plasma Science 30 (2002) 808-818

[7] G. Gantenbein et al., this conference, paper IT/2-4Re

[8] K. Felch, M. Blank, P. Borchard, P. Cahalan, S. Cauffman, T.S. Chu and H. Jory, *Journal of Physics: Conference Series 25 (2005) pp. 13-23.*

[9] Kopp, K.W.; Kasparek,W.; Holzhauer, E.: *Int. J. Infrared Millimeter Waves 13 (1992) 1619 – 1631*

[10] B. Plaum, G. Gantenbein, W. Kasparek, K. Schwörer, et al., J. Phys.: Conf. Ser. 25 (2005) 120-129

[11] W. Bin, A. Bruschi, V. Erckmann, F. Gandini, et al., to be published in: Proc. 24th SOFT Warsaw, Poland, 2006