The 10 MW ECRH and CD System for W7-X

V. Erckmann[1], H. Braune[1], H. P. Laqua[1], G. Michel[1], G. Dammertz[2], M. Thumm[2], G. Gantenbein[3], W. Kasparek[3], G. A. Mueller[3], and the W7-X ECRH teams at IPP, FZK and IPF

[1] *Max-Planck-Institut für Plasmaphysik, Teilinstitut Greifswald, Association EURATOM, Wendelsteinstr. 1, D-17491 Greifswald, Germany*
[2] *Forschungszentrum Karlsruhe, Association EURATOM-FZK, Institut für Hochleistungsimpuls- und Mikrowellentechnik, Postfach 3640, D-76021 Karlsruhe, Germany,*
[3] *Institut für Plasmaforschung, Universität Stuttgart, Pfaffenwaldring 31, D-70569 Stuttgart, Germany*

Abstract. Electron Cyclotron Resonance Heating (ECRH) is the main heating method for the Wendelstein 7-X Stellarator (W7-X), which is the next step device in the stellarator line of IPP and is presently under construction in the Greifswald branch of IPP. The experiment aims at demonstrating the inherent steady state capability of stellarators at reactor relevant plasma parameters. W7-X (major radius 5.5 m, minor radius 0.55 m) is equipped with a superconducting coil system operating at 3 T for steady state operation and a divertor for 10 MW steady state heat removal. A 10 MW ECRH plant with CW-capability at 140 GHz is under construction to meet the scientific objectives. The microwave power is generated by 10 gyrotrons with 1 MW each. A European R&D program aiming at the development of a prototype gyrotron for W7-X has been successfully terminated by fall of 2002. A prototype gyrotron with the same specifications was developed for W7-X at CPI (USA). Test results and limitations are reported. The distinct microwave beams from each gyrotron are combined and transmitted to the W7-X Stellarator ports by an open quasi-optical transmission system with high transmission efficiency, which runs at normal pressure and consists of water cooled imaging mirrors. Cold tests of a full size, uncooled prototype line and the related RF-diagnostics are presented. The microwave power is launched to the plasma through 10 synthetic diamond barrier windows and in-vessel quasi-optical plug-in launchers, which allow an independent steering of each beam. The commissioning of the ECRH plant is well under way and the status is presented.

INTRODUCTION

ECRH is the main heating system for steady-state operation of W7-X (up to 30 min) in the reactor relevant long-mean-free-path transport regime. A heating power of 10MW is required to meet 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. High density operation above the X2 cut-off density at 1.2 10^{20} m^{-3} will be obtained with 2nd harmonic O-mode as well as via O-X-B mode conversion heating [2,3]. The physics requirements ask for an ECRH system, which is capable of

- arbitrary toroidal launch (current drive, O2-mode, O-X-B conversion)
- arbitrary poloidal launch (on- and off-axis heating)
- arbitrary wave polarization (e.g. elliptical for oblique launch)
- high- and low field side launch (phase space physics)
- AM capability (heat waves and switching experiments)

The ECRH system features a modular design consisting of 10 gyrotrons (two subgroups of 5 gyrotrons each) at 140 GHz with 1 MW, CW output power each. The development of gyrotrons with the required performance was successfully completed recently in Europe. The European R&D programme was launched in 1998 as a combined effort of several research laboratories and Thales Electron Devices as the industrial partner [4]. Also in 1998 a contract was placed with CPI (USA) to develop in parallel a W7-X gyrotron based on the same specifications. Recent test results are reported in Sec.2. An optical transmission system was chosen for W7-X, which is based on the excellent experience at W7-AS [5]. It turned out to be the most simple, reliable and cost effective solution. The overall-design of the ECRH-system is described in [6], the conceptual design of the optical transmission lines which guide the millimetre wave power from the gyrotrons to the steerable antennas inside the plasma vessel is given in [7]. The transmission characteristics of the system are discussed in Sec. 3 and compared with first experimental results obtained on a prototype system.

2. THE W7-X GYROTRON

2.1 Design parameters

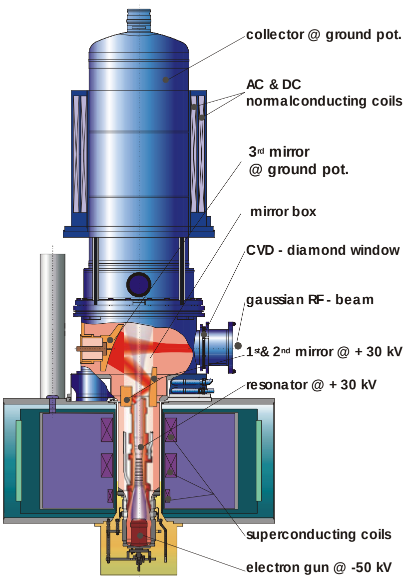
The design parameters of the W7-X gyrotron are summarized in Table 1 and incorporate technologies, which were not state of the art at the time of the definition:

Cavity mode	$TE_{28.8}$
RF output power	1 MW
Frequency	140.3 GHz
Accelerating voltage	81 kV
Beam current	40 A
Mode purity of cavity	98.8 %
Retarding collector voltage	> 25 kV
Power modulation depth	0.3-1 MW
Modulation frequency	up to 10 kHz
Average velocity ratio	1.3

TABLE 1:
Gyrotron design parameters

The gyrotron uses a diode-type magnetron injection gun, which operates at V_{acc} = 81 kV with respect to the body (beam tunnel, cavity, quasi-optical launcher and the first two mirrors) and at a current of I_b = 40 A, corresponding to a cathode current density j_c = 2.5 A/cm. A schematic view of the gyrotron is shown in Fig. 1.

The cylindrical cavity is designed for operating in the $TE_{28,8}$-mode with a diffractive quality factor of 855 in cold cavity approximation and of 1100 in a self-consistent calculation. The (cold-cavity) frequency is designed to operate at 140,3 GHz to compensate for the frequency downshift during power loading of the cavity. The magnetic field at the cavity is 5.56 T. The cavity is made of dispersion strengthened copper (Glid-cop), the peak wall losses are below 2 kW / cm^2 at 1 MW output power. The RF-beam is separated from the electron beam through a highly efficient quasi-optical mode converter consisting of a rippled-wall, helically-cut waveguide launcher [8] followed by a 3 mirror imaging system for beam shaping. The output window unit uses a single, edge cooled CVD-diamond disk with an outer diameter of 106 mm, a window aperture of 88 mm and a resonant thickness of 1.8 mm. The calculated absorbed power for tanδ = 2.10^{-5} is 353 W, the window temperature saturates with a time constant of 5 s.



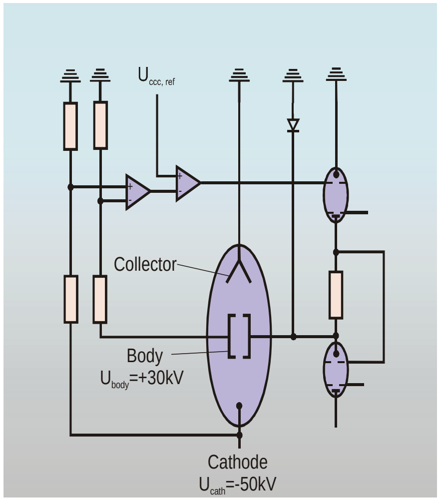


FIGURE 1: Sketch of the W7-X gyrotron

FIGURE 2: Electric circuitry of the Gyrotron

The collector, the mirror box with the output window and the third mirror are on ground potential. At the nominal depression voltage, the cathode is at –50 kV. The beam tunnel, cavity, the quasi-optical launcher and the first two mirrors have the depression potential of +30kV as seen from Fig.2.

2.2 Test results of the TED gyrotron at FZK

The RF beam is injected into an RF-tight microwave chamber which is equipped with two water-cooled polarization mirrors and two water-cooled deflecting mirrors directing the beam towards the 1 MW CW water load [9]. The surface of the first deflecting mirror contains a grating, which reflects a small power fraction towards a horn antenna and detector for in-situ monitoring of the rf-power with a spectral resolution of 100 MHz. The power in short pulse operation was measured by a calorimeter. The power in long pulse operation is determined by the calorimetric measurement of the CW-load. All components of the microwave chamber are watercooled and detailed measurements of different loss channels were performed by calorimetric measurements [4].

Fast RF power modulation can be achieved by modulating the accelerating voltage. For heat wave experiments, the gyrotrons are specified for an output power modulation between 0.3 and 1 MW with a sinusoidal frequency of up to 10 kHz. Assuming an output power of 1 MW and a gyrotron efficiency (with depressed collector) of 45 %, the power loading of the collector will be 1.2 MW. This value would increase to 2.1 MW for a reduced output power of 100 kW, if only the depression voltage is modulated, which is beyond the CW power-handling capability of the collector. Calculations of the behavior of the electron beam show that power modulation is possible without changing the depression voltage up to a least 25 kV, the collector loading, however, is strongly reduced. Experimental data are shown in Fig. 3.

The loading is almost constant over the whole output power range. The increase is less than 6% at a low output power of 100 kW, and the power at the collector is kept below 1.3 MW. Good agreement between measured and calculated data is found.

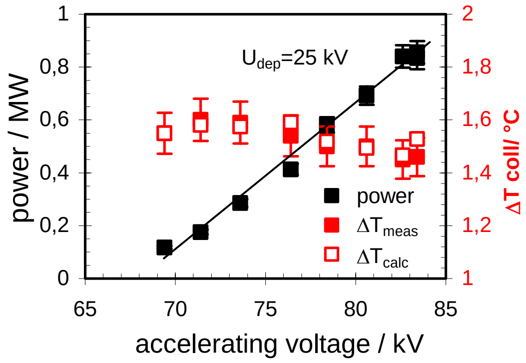


FIGURE 3: Output power and collector loading as a function of the acceleration voltage at constant depression voltage.

At intermediate pulse lengths (55 s) an output power of 920 kW was measured. A somewhat reduced output power of 890 kW was measured at pulse lengths of 180 s with an efficiency of 41% at a depression voltage of about 29 kV. It should be noted, that 180 s is the test stand limitation for currents in excess of 25 A.

To explore the cw-capability of the gyrotron we have extended the pulse duration within the test-stand limitations for cw-operation (< 25 A beam current). 0.54 MW was achieved for 15 min pulse duration at 39 % efficiency. The pulse duration was limited by internal outgasssing of the gyrotron, which originated from overheating of some parts (e.g. ion-getter pumps). Improved cooling will be incorporated in the series gyrotrons.

2.3 Test results of the CPI gyrotron at the factory

The gyrotron is shown in Fig. 4 (left). Factory tests of the W7-X-Gyrotron from CPI were recently completed within the test stand limitations. The test stand is capable of short pulse operation in the ms-range at full current and of CW-operation at a beam current < 25 A. An output power of 920 kW was achieved in 3 ms pulses with 80 kV accelerating voltage (20 kV depression voltage) and 38 - 45 A beam current, the efficiency is about 37 %. Extensive measurements on power control, power modulation and operation regimes were performed with short pulses. An example is shown in Fig. 4 (b), were the RF-power is plotted as a function of the cathode voltage without collector voltage depression. Further results are reported elsewhere in this volume. An output power of 500 kW was achieved with very good reliability in repetitive long pulse experiments (10 min) with reduced beam current of 25.6 A. The tube is ready for shipment, further tests towards full power, long pulse operation are foreseen at IPP Greifswald, where the power supply has full power CW capability.

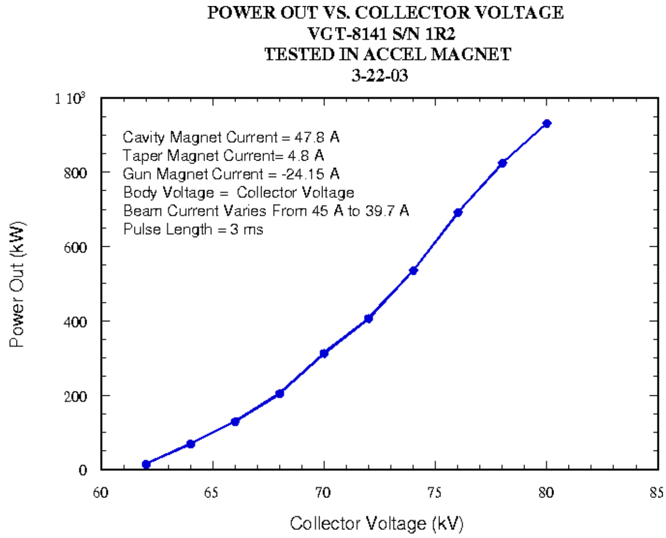


FIGURE 4: CPI Gyrotron (left) and output power vs. Collector voltage w/o depression voltage (right)

3. TRANSMISSION LINE

3.1 General considerations

For the high-power transmission of millimeter waves, free-space beam waveguides as well as highly oversized corrugated tubular waveguides are used [10]. Owing to good experiences with a 800 kW / 140 GHz beam waveguide [10] on the stellarator W7-AS, a quasi-optical transmission system was chosen for W7-X as a low-cost solution with high efficiency. In contrast to tubular waveguide transmission, problematic matching sections between the gyrotron output beam and the waveguide, and back to the optical launcher in the plasma vessel are avoided. In a beam waveguide, the millimeter waves are transmitted as Gaussian beam by iterative transformation with focusing elements [11,12], usually metallic mirrors. The design of such mirrors is relatively simple and straightforward.

The main advantages of this technology are low ohmic and diffractive losses, high power capability due to relatively low field strength, and inherent mode filtering as high-order modes are diffracted out of the system. A major disadvantage of a beam waveguide is the large diameter of the beam and thus the required size of the mirrors governed by diffraction of the beam. Therefore, systems with several channels are complex and become bulky. To overcome this disadvantage, a confocal Multi-Beam-Waveguide (MBWG) has been developed for the ECRH system on W7-X. Here, several quasi-optical beams are transmitted by a common mirror system. At the input plane of the MBWG, the purely Gaussian 140 GHz beams are closely packed and parallel. The MBWG consists of four focusing mirrors at distances of two focal lengths (and additional plane mirrors to straighten the beam path). It must simultaneously offer a low-loss propagation of all on-axis and off-axis beams and a correct imaging from the input to the output plane. After the first mirror, all beams cross in its focal plane. Behind the focal plane of the second mirror, the beams are parallel again, and the input beam configuration is recovered, rotated by 180°. The mode analysis however yields a purity of only 96.1 %. After four mirrors, the spurious modes have cancelled and the beams cross the output plane exactly perpendicularly in the nominal position, which is documented by a mode purity of 99.8%. Further calculations [13] show, that even a much higher number of beams could be transmitted via a common mirror system without remarkable diffraction loss.

3.2 Engineering design

The design of the ECRH system had a strong impact on the design of the building for W7-X. The 10 gyrotrons (plus two optional tubes) and the auxiliary systems for operation (high-voltage supplies, water cooling, liquid helium and liquid nitrogen supplies for the superconducting gyrotron magnets etc.) are placed in the ECRH building adjacent to the central W7-X experimental hall. The tubes are installed in two rows symmetrically to a central beam duct, which connects the ECRH hall with the stellarator. The gyrotrons located behind the wall of the duct radiate their power laterally through small holes in the wall. For each gyrotron, a beam conditioning optics consisting of five mirrors is mounted on a common base frame, which is alreadyinstalled in the beam duct and is shown in Fig. 5 (left).

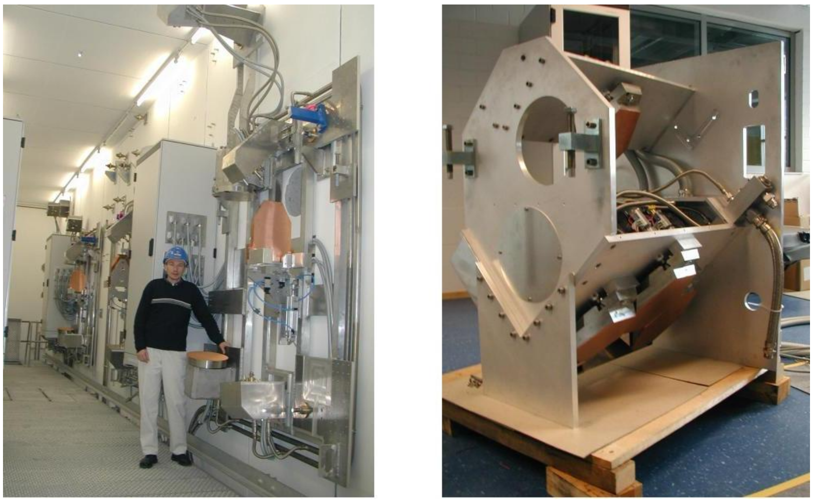


FIGURE 5. Single beam mirrors: The single beam unit consists of 3 mirrors and two polarizers mounted on a base frame (left). The beam-combining optics module is shown on the right.

Two mirrors match the gyrotron output to a Gaussian beam with the correct beam parameters. The following two mirrors have sinusoidally corrugated surfaces [14] to set the polarization needed for optimum absorption of the radiation at different heating and current drive scenarios. The first of these polarizers (elliptical polarizer, groove period = 1.28 mm, depth = 0.56 mm) shifts the phase between the orthogonal components of the

TE-wave by 90°, thus any ellipticity of the reflected radiation can be set by proper rotation of the mirror. A second polarizer (polarization rotator, period = 1.28 mm, depth = 0.80 mm) has a corrugation for a 180° phase shift to rotate the axis of the polarization ellipse to the appropriate orientation. Finally, a fifth mirror focuses the beam to a plane mirror array (Beam Combining Optics, BCO) as seen from Fig.5 (right), which is situated at the input plane of the MBWG. The MBWG is designed to transmit up to seven beams (five 140 GHz beams, one 70 GHz beam plus an additional spare one) from the gyrotron area (input plane) to the stellarator (output plane).

In addition to the four focusing mirrors mentioned above, three more plane mirrors are used to fit the transmission lines into the W7-X buildings. Two symmetrically arranged MBWGs transmit the power of all gyrotrons over a distance of 45 m, the total lengths of the transmission lines are 57 to 65 m depending on the locations of the corresponding gyrotron and torus port. At the output plane of the MBWG, a beam distribution mirror array (see Fig. 6 (left)) separates the individual beams and directs each of them via two mirrors and through a vacuum barrier window towards the plug in launcher with the movable antennas. Four large ports of W7-X will be equipped with the plug in launchers.

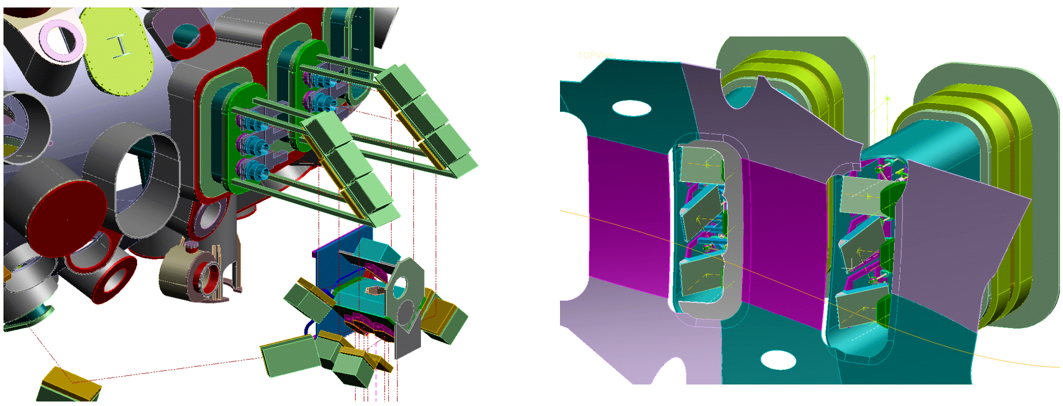


FIGURE 6: Design of the beam distribution optics unit (left) and plug-in launchers with movable mirrors (right)

The in-vessel launching mirrors can be independently moved within a wide poloidal and toroidal angular range to meet the requirements for optimum current drive (typically at 15 ° toroidal angle), O-X-B launch (at 35 ° toroidal angle) and off-axis heating ($\pm$ 30 ° poloidal angle). The design is seen from Fig. 6 (right).

For beam diagnostics and power measurement, directional couplers, infrared cameras, calorimetric loads and CW dummy loads are installed.

3.3 Mirror design

To minimise surface deformations due to thermal loading by the ohmic losses, thermo--mechanical calculations have been performed for several materials or combinations thereof. The design which was finally chosen consists of a 60 - 70 mm thick honeycomb structure from stainless steel and a thin (2 mm) layer of electroformed copper on the mirror surface. The cooling channels are located directly below the copper and form one or several spirals going from the centre (water inlet) to the edge of the mirror (water outlet(s)). The width and depth of the spirals are adapted to the size of the mirrors and the gaussian distribution of the heat load. A very low thermal deformation below 10^{-3} m^{-1} was confirmed experimentally. The photograph in Fig. 7 displays a prototype mirror fixed to its mount with the copper surface partly removed to show the cooling channel.

FIGURE 7: Single beam mirror with the Cu-SS sandwich structure and cooling channels.

FIGURE 8: MBWG-mirrors in the beam duct

Fig. 8 shows the installation of MBWG-mirrors in the beam duct. The polarizers, which are the most loaded mirrors as well as standard single beam mirrors for beam matching were installed in the gyrotron test stand at FZK Karlsruhe and have passed tests successfully under CW, high power conditions.

3.4 Transmission efficiency

The overall transmission efficiency is determined by several loss channels. Besides ohmic dissipation on the mirrors and diffraction loss due to mode conversion and mirror surface deformation as discussed before, further sources of loss are beam truncation by the reflectors and windows, misalignment, and atmospheric absorption. Additionally, conversion losses from the gyrotron output beam to a purely Gaussian beam have to be taken into account. The estimated contributions are listed in Table 2. One can see, that a total transmission efficiency of at least 85 % is expected. Furthermore, stray radiation of the order of 5-10 % arising from diffraction losses inside the gyrotron has to be absorbed by water-cooled absorber panels and the concrete walls of the beam duct. The ECRH system for W7-X will finally comprise more than 160 water-cooled, remote steerable mirrors for beam matching and polarization adjustment, transmission, switching of beams, and for the launchers. Due to the complexity of the system and to test its performance and stability, a full-scale, uncooled prototype was built. Within the experimental uncertainties the results of low power tests are in good agreement with the calculations. The total transmission efficiency of the prototype system including the diffraction due to imperfect surfaces, ohmic loss, typical misalignment, and atmospheric absorption was checked by calorimetric measurements and yielded 90±2 %. This is in good agreement with the theoretical value for the prototype system, which is 92 %. From amplitude and phase measurements of the various beams at the output of the MBWG, a mode purity between 97 % and 99 % was deduced.

Loss channel	Elements	Loss
Output mode transformation loss	Output beam	≤ 2%
Absorption on mirrors	16 copper surfaces	3 %
Diffraction and beam truncation	16 reflectors	2 %
Misalignment	Transmission line	2 %
Atmospheric absorption	60 m dried air	0.8 %
Beam truncation of launcher	1 vac. window + 2 int. mirrors	3 %
TOTAL LOSS		≤12 %

TABLE 2: Contributions to transmission loss for the ECRH system on W7-X.

4. SUMMARY AND CONCLUSIONS

The ECRH heating and current-drive system for W7-X is presently under construction. An RF-power of 10 MW at 140 GHz in CW-mode will satisfy the needs in the first stage of W7-X operation to meet the scientific objectives. The system is designed for high flexibility with respect to wave coupling and fast power control. All major heating and current-drive scenarios such as X2-mode, O2-mode and mode-conversion to Bernstein modes are accessible with the optical in vessel laucher in combination with the relevant choice of the wave polarization. Prototype gyrotrons with the required performance were successfully developed and in Europe and USA and have passed preliminary tests. Further improvements are under way. It has been shown that multi-beam waveguides offer favourable transmission characteristics for millimeter waves. The shape and configuration of the metallic reflectors can be optimised for low mode conversion. The application of this technique for the ECRH system on W7-X leads to a relatively compact solution, consisting of modular matching optics for each gyrotron, common beam transmission via two MBWGs through an underground duct, and individual antenna optics with high transmission efficiency. The most loaded components were successfully tested under high-power, CW conditions in the test stand at FZK. The project has now entered the phase of series installation and commissioning.

REFERENCES

[1] V. Erckmann, H.J. Hartfuß, M. Kick, H. Renner, J. Sapper, F. Schauer, E. Speth, F. Wesner, F. Wagner, M. Wanner, A. Weller, and H. Wobig,: The W7-X project: Scientific Basis and Technical Realization. Proc. 17th IEEE/NPSS Symposium on Fusion Engineering, San Diego, USA (1997). Ed. IEEE, Piscataway, NJ 1998, 40 - 48

[2] V. Erckmann, and U. Gasparino: Electron cylotron resonance heating and current drive in toroidal fusion plasmas. Plasma Phys. Control. Fusion 36 (1994) 1869 – 1962

[3] H. P. Laqua, V. Erckmann, H.J. Hartfuß, H. Laqua, W7-AS Team, and ECRH Group:
Resonant and nonresonant Electron Cyclotron Heating at Densities above the Plasma Cut off by O-X-B Mode Conversion at the W7-AS Stellarator,
Phys. Rev. Lett. **78**, 3467 (1997)

[4] G. Dammertz, et al. IEEE Trans. Plasma Science 30 (2002) 808-818

[5] V. Erckmann, G. Dammertz, W. Kasparek, H.P. Laqua, H. Maaßberg, M. Thumm, W7-X and W7-AS teams at IPP Garching: ECRH and ECCD experiments at W7-AS, Status at W7-X, Fusion Eng. Design 53 (2001) 365 – 375

[6] V. Erckmann, T. Geist, H.P. Laqua, M. Weißgerber, L. Empacher, W. Förster, G. Gantenbein, W. Kasparek, G.A. Müller, P.G. Schüller, K. Schwörer: ECRH system for the W7-X stellarator. In Proc. of the 20th Symposium on Fusion Technology, Marseille, France, (1998), FUSION TECHNOLOGY 1998, Vol. 1, 299-302

[7] L. Empacher, W. Förster, G. Gantenbein, W. Kasparek, G.A. Müller, P.G. Schüller, K. Schwörer, U. Schumacher, D. Wagner, V. Erckmann, T. Geist, H.P. Laqua: Conceptual Design of the 140 GHz / 10 MW CW ECRH System for the Stellarator W7-X. Proc. of the 19th Symp. on Fusion Technology, Lisbon, Portuga1, (1996), FUSION TECHNOLOGY 1996, Vol.1, 541-544

[8] G.G.Denisov et al., " 110 GHz gyrotron with a built-in high-effeciency conerter", Int.J.Electronics 72, pp. 1071-1091,1992

[9] R.L. Ives et al.,"Development of a 1 MW CW Waterload für Gaussian Mode Gyrotrons", Conf. Digest 23rd Int. Conf. Infrared Millimeter Waves, Colchester (UK), pp. 226-227, 1998.

[10] Thumm, M., W. Kasparek: Passive high-power microwave components, IEEE Trans. on Plasma Science, PS-30, 755-786 (2002).

[11] Grau, W. in Kleen, W. and Müller, R.: Laser. Berlin: Springer 1969.

[12] Goldsmith, P.F.: Quasi-optical Systems. New York: IEEE Press, Chapman and Hall, Publishers, ISBN 0-7803-3439-6, 1998

[13] Empacher, L. and Kasparek, W.: Analysis of a multiple-beam waveguide for free-space transmission of microwaves. IEEE Trans. Antennas Propagat., Vol. AP-49 (2001) 483 - 493

[14] Kopp, K.W.; Kasparek,W.; Holzhauer, E.: Microwave reflection properties of grooved metallic mirrors. Int. J. Infrared Millimeter Waves 13 (1992) 1619 - 1631