ECRH For W7-X: Status And Relevance 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.

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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 $T_e = 2\text{-}10$ keV, $T_i = 2\text{-}5$ 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. High-density operation above the X2 cut-off density at $1.2\ 10^{20}\ m^{-3}$ is accessible with O2-mode ($< 2.5\ 10^{20}\ m^{-3}$) and at even higher densities with O-X-B mode conversion heating [2,3]. 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, the similarities are obvious with the ITER installation having about twice the power:

TABLE 1. 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

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 operation 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. The demonstration of the full power CW-capability of one module is therefore a major milestone in the ECRH-project and was achieved recently An optical transmission system was developed for W7-X, which is 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 multi-beam mirror lines, each of them combining and handling 5 (+2) individual RF-beams (7 MW). The power handling capability has inherently a large safety margin (factor of 2-3) due to the low power density on the mirror surfaces, which keeps the option open 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 satisfies the ITER-ECRH (24 MW) power capability demands without modification. 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.

INTEGRATED HIGH POWER, CW TESTS

The development of the W7-X Gyrotrons started in 1998 in Europe with Thales Electron Devices (TED) and in USA with CPI as industrial partner. Results from the two R&D tubes from TED are reported in [6]. The year 2005 saw the successful full performance tests of Gyrotrons from both manufacturers, CPI and TED: The final tests of the CPI gyrotron and the 1st series Gyrotron from TED (see Fig.1) were completed in May and September 2005, respectively, at IPP.

FIGURE 1. The TED SNo.1-Gyrotron under test.

The test arrangement was similar for both Gyrotrons: The microwave beams were transmitted through 7 single beam mirrors of the transmission system into a calorimetric CW-load to perform integrated tests of one module of the ECRH system. The beam path is seen from Fig. 2. The Gyrotron beam enters the beam duct through a hole in the concrete wall and hits both beam-matching mirrors (M1, M2), the set of polarizers (P1, P2), and is then directed towards the dummy load via the beam combining optics (BCO) and a special mirror (MD). By proper adjustment of the related mirror in the BCO, the beam can be coupled to the first mirror (M5) of the Multi-Beam Waveguide (MBWG). The CW-dummy loads are seen in the foreground. A special optical arrangement with retro-reflectors mounted in the symmetry-plane of the mirror line (i.e. at half distance of the MBWG) is being prepared for full performance tests of the full distance transmission via the MBWG. This is necessary, because the optical elements in the torus hall can be installed only in a late phase of the W7-X-torus assembly. The front end optic of the transmission line including the front steering launcher and the in-vessel mirror components are presented in detail in ref [4].

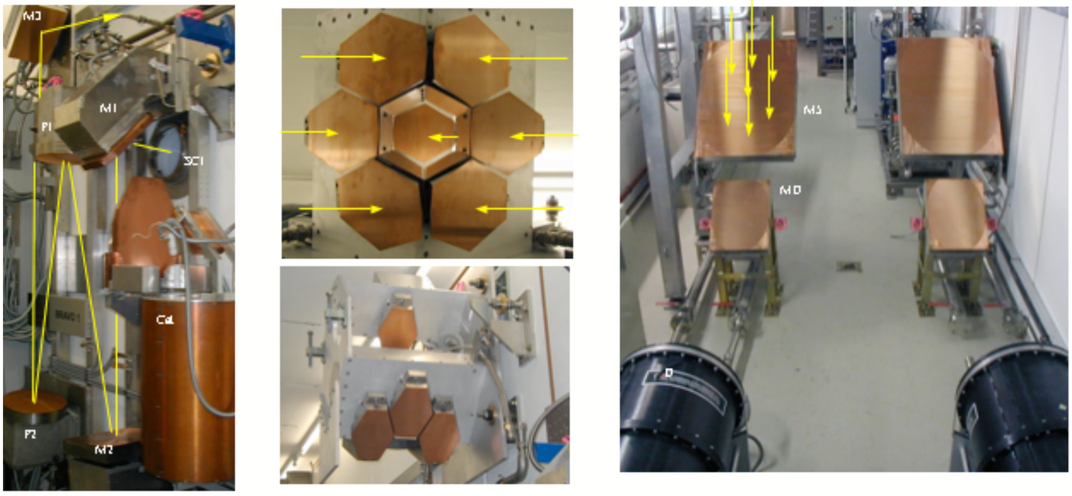

FIGURE 2. The quasi-optical transmission system under test at IPP. The beam path is indicated. Left: Single beam section with BMO (M1,M2), short-pulse calorimeter (Cal) and polarizers (P1,P2) mounted on a common base frame. Middle: The Beam Combining Optics handles 7 individual beams. Right: First mirror (M5) of the Multi-Beam-Waveguide with a special launching mirror (MD) to steer each individual beam towards the CW-load(s) in the foreground.

It is worth noting, that all peripheral systems at IPP like main PS, central cooling system, body-modulator, transmission line components, RF-diagnostics, as well as the central control and data-acquisition system are new and had to go through this integrated qualification process together with the gyrotron.

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. 3 (left). 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 measured parameters became stationary.

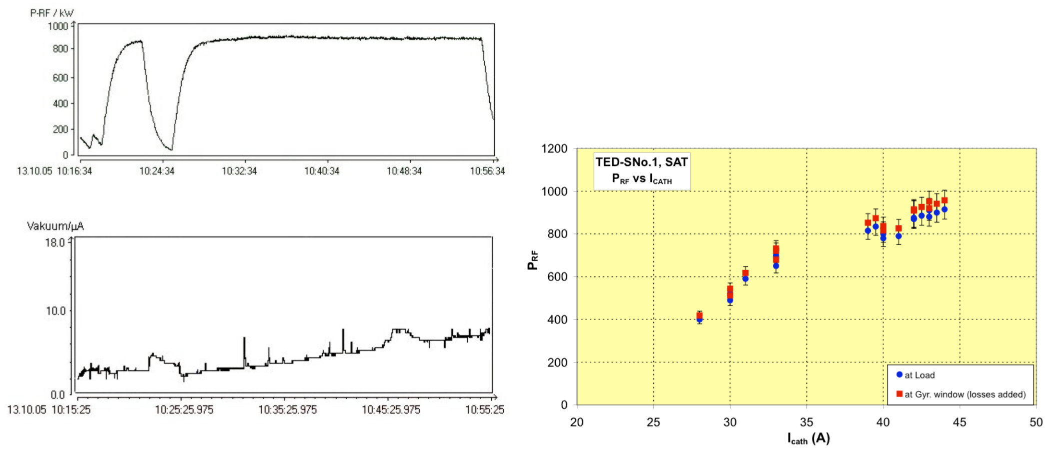

Figure 3. Test data for the TED SNo.1 Gyrotron. Left: RF-power (top) and gyrotron vacuum (GIP-current) as a function of time (h,min,sec). Right: RF-power in the cw-load (dots) and at the Gyrotron window with transmission losses added (squares) as a function of the beam current.

An example for a beam-current scan is shown in Fig. 3 (right), each data point was taken in pulses in the range of 1-5 min pulse duration to save experimental time. The scan was performed up to a maximum output-power of 0.96 MW with an efficiency of 44 %, indicating the Gyrotron capability. We have chosen somewhat more conservative parameters for the 30 min operation, which is the target operation time for W7-X. The Gyrotrons were operated at a source power in the directed beam of about 0.9 MW (CPI) and 0.92 MW (TED), the related power measured in the calorimetric CW-load was 0.83 MW (CPI) and 0.87 MW (TED). 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 (BMO) had to be accepted as compared to the TED-Gyrotron (50 kW). 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.

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.

With the encouraging results from the integrated tests of two modules, series production and commissioning of the major system components was released. The actual status (April 2006) is given in Table 2.

TABLE 2. ECRH for W7-X, commissioning of main components, status April 2006

	Total (units)	Status
Main PS (32 MVA)	10	8 operational
Body Modulator/Crowbar	10	6 op.
Cooling plant (Gyrotrons)	10	10 op.
Cooling plant (transmission line)	2	2 op.
Transmission (SBWG)	10	10 op.
(MBWG)	2	2 op.
Gyrotrons	10	3 op. (+2 under test)
Gyrotron-Magnets	10	10 op.
Launcher	4	Mock-up tests
ECRH-towers (beam distribution)	2	Design
In-vessel components		Design, test

The ECRH-system served already as a high power test bed for ITER ECRH-components, which were developed at different laboratories under EFDA umbrella. 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 test-programs: The mock-up version of a remote steering launcher, which is an option for the ITER upper launcher, was tested under high power conditions at IPP-Greifswald [7]. High power, short pulse tests of a mock-up version of a 2 MW calorimetric load were also successfully performed recently [8].

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, which runs on time and budget. 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, while keeping in mind, that the ITER-system must satisfy additional requirements such as operation and maintenance in a radioactive environment.

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