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The 10 MW ECRH and CD System for W7-X: Status and first tests

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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 10 MW 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 2^{nd} harmonic O-mode as well as O-X-B mode conversion heating [2]. The ECRH system features a modular design consisting of 10 gyrotrons at 140 GHz with 1 MW, CW output power each. A European R&D programme was launched in 1998 as a combined effort of several research laboratories and Thales Electron Devices (TED) as the industrial partner [3]. Also in 1998 a contract was placed with CPI (USA) to develop in parallel a W7-X gyrotron based on the same specifications.

The design parameters of the TED W7-X gyrotron are summarized in Table 1. The (cold-cavity) frequency is 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 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 [4] 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 and a window aperture of 88 mm. The collector, 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 about +30 kV.

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
Operation-Mode	CW

Table 1: Gyrotron design parameters

Fig. 1: The TED-Prototype gyrotron at IPP Greifswald

For the **TED prototype** (see Fig.1) 920 kW were measured with a calorimeter for 55 s and 890 kW for 180 s with an efficiency of 41% at a depression voltage of about 29 kV. 180 s pulse duration is the test stand limitation for currents in excess of 25 A. The cw-capability of the gyrotron was explored within the FZK test-stand limitations (< 25 A beam current) and 0.54 MW was achieved for 15 min pulses 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 seven TED series gyrotrons, which were ordered in 2003 with a typical delivery sequence of 3 tubes per year. The TED-prototype operates routinely at IPP since Nov. 03 and is used for high-power transmission line component tests.

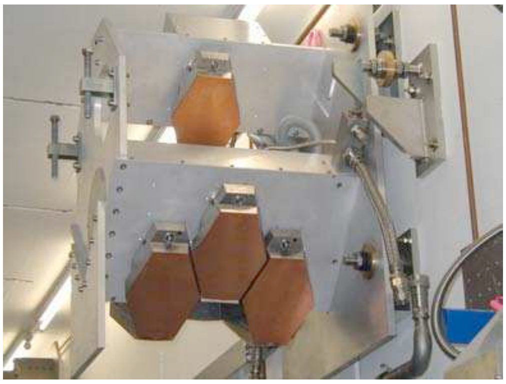
Factory tests of the **CPI-gyrotron** were completed within the CPI test stand limitations. Only short-pulse operation in the ms-range is possible at full current, CW-operation is possible at a beam current < 25 A. An output power of 920 kW was achieved in 3 ms pulses with 80 kV accelerating voltage (20 kV depression voltage) and 38-45 A beam current, the efficiency is about 37 %. An output power of 500 kW was achieved with very good reliability in repetitive 10 min pulses with reduced beam current of 25.6 A. The tube is presently under test at IPP, where the power supply has full power, CW capability.

The 10 gyrotrons (plus two optional 70 GHz 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. Two sets of subsystems are completed and operational, the others are being installed step by step. The tubes are installed in two rows symmetrically to a central beam duct, which connects the ECRH hall with the stellarator (Fig. 2, right) and radiate their power laterally through small holes in the wall.

An optical transmission system was chosen for W7-X, which is the most simple, reliable and cost effective solution [5]. For each gyrotron, a single-beam waveguide section (SBWG) consisting of five mirrors is mounted on a common base frame. All SBWG modules are already installed in the beam duct, some of them are shown in Fig. 2 (left). Two mirrors match the gyrotron output to a Gaussian beam, two corrugated mirrors set the polarization and a fifth mirror focuses the beam to a plane mirror array (Beam Combining Optics) as seen from Fig.3 (left), at the input plane of the multi beam waveguide (MBWG).

Fig. 2. Single beam mirror modules (left) and multi beam waveguide (right).

Each of the two MBWG's (see Fig. 2, right) transmits up to seven beams (five 140 GHz beams, one 70 GHz beam plus one spare) from the gyrotron area (input plane) to the stellarator (output plane). The MBWG consists of four focusing mirrors at distances of two focal lengths (and additional plane mirrors to straighten the beam path). It provides a correct imaging from the input to the output plane, where a beam distribution mirror array separates the individual beams (see Fig. 3 right). Each of them is directed via two mirrors and through a CVD-diamond vacuum barrier window towards the plug in, wide angle, front steering launcher. Four large ports of W7-X will be equipped with the plug in launchers. The total lengths of the transmission lines are 57 to 65 m depending on the locations of the corresponding gyrotron and torus port. The overall transmission efficiency is determined by ohmic dissipation on the mirrors, diffraction loss due to mode conversion and mirror surface deformation, 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. A full-scale, uncooled prototype was built to test the system performance and stability. The results of low power tests yielded 90±2 % in good agreement with the theoretical value of 92 %. for the prototype system.



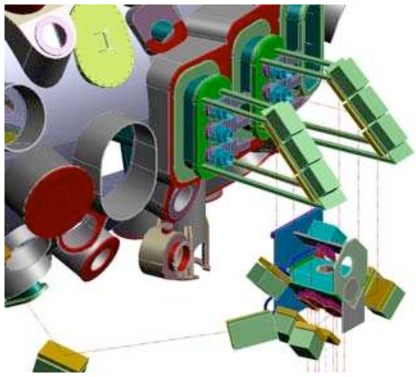


Fig. 3: Beam combining optics unit (left) and design of the beam distribution and feeding system for the front-steering launcher (right)

The optical in vessel laucher in combination with the relevant choice of the wave polarization covers all major heating and current-drive scenarios such as X2-mode, O2-mode and mode-conversion to Bernstein modes. Prototype gyrotrons with the required performance were successfully developed and tested in Europe and USA. Two gyrotrons are operating on site at Greifswald. The multi-beam waveguides offer favourable transmission characteristics for millimeter waves, the most loaded components were successfully tested under high-power, CW conditions in the test stand at FZK and on site at IPP-Greifswald. 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 project has now entered the phase of series production, installation and commissioning and integrated tests.

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