PERFORMANCE OF THE 70 GHz ECRH SYSTEM ON W VII-A

R. Wilhelm, V. Erckmann, G. Janzen, W. Kasparek,
G.A. Müller. P.G. Schüller, M. Thumm
Institut für Plasmaforschung, Universität Stuttgart, Stuttgart, W. Germany

W VII-A Team*
Max-Planck-Institut für Plasmaphysik, EURATOM-Assoc., Garching, W. Germany

1. Introduction

During a three year period, extensive ECRH investigations were performed on the Garching W VII-A stellarator. The experiments were started in 1983 using a single 28 GHz/200 kW/40 ms pulse gyrotron and were continued with a 70 GHz/ 200 kW/100 ms system until November 1985. In both cases, initial experiments were started by radiating the unpolarized gyrotron waves (mainly the TE02 mode) through an oversized circular waveguide (length almost 30m, including one 90°-bend) directly into the torus. In further steps, the TE02 wave was transformed into the almost perfectly linearly polarized HE11 hybrid mode in the conversion sequence TE02→TE01→TE11→HE11 [1,2]. The resulting narrow millimetre-wave beam was launched perpendicularly to the magnetic field from the low-field side in O-mode orientation ($\vec{E} \parallel \vec{B}$) for heating at the fundamental frequency and in X-mode polarization ($\vec{E} \perp \vec{B}$) for harmonic heating [3]. Almost 20,000 plasma discharges (approximately 8,000 at 28 GHz and about 11,000 at 70 GHz) resulted in a lot of information concerning physics and techniques of ECRH applications. A summary of the recent physical results is given at this conference*, while the following sections describe the technical features and the performance of the 70 GHz system.

2. Microwave Source

At either frequencies (28 GHz, 70 GHz) commercial pulse gyrotrons were used. Careful control of the various parameters (magnetic field geometry, gun anode voltage, collector voltage and current of the electron beam) turned out to be the basic requirement for stable tube operation at the ultimate parameter set for maximum output power at highest achievable mode purity. The instability of the parameter settings has to be in the range of $\leq 10^{-3}$. High precision high voltage supplies for the collector voltage (80 kV) (developed at IPP Garching) and the gun anode voltage (developed by IPF Stuttgart) were used [4]. Programming the gun anode voltage allows a fast modulation of the gyrotron microwave power (0-10 kHz). Square wave modulation of the gyrotron output power (frequency range 100 to 600 Hz at 10-30% modulation degree) allowed heat wave experiments on the plasma to analyze thermal transport [5].

3. Transmission Line Components

Low-loss power transmission from the microwave source to the plasma device and mode transformation to achieve a narrow and linearly polarized beam are basic requests for optimum ECRH applications. For this purpose various waveguide components are required, which were developed and systematically improved by the IPF Stuttgart. The following table gives an overview of the

---

*) see V. Erckmann et al.: "ECRH in the Wendelstein VII-A Stellarator", invited paper at this conference.

basic components in the 70 GHz transmission line and their purpose.

component	waveguide mode	purpose	typical losses
(gyrotron)	≈ 95% TE02	(power source)	≤ 5% TE03,TE13
down-taper	TE02	reduction of gyrotron output waveguide diameter from 63.5 mm to 27.8 mm	< 0.1%
corrugated bend	TE02	gradual 90°-bend with sinusoidal curvature	≤ 1.5%
mode converter	TE02→TE01	transformation into low-loss transmission mode	0.5%
mode filter	TE01	attenuation of spurious TEmn (m≠0) modes by 90-99%	≤ 2%
mode converter	TE01→TE11	transf. into almost linearly polarized mode	≤ 6%
mode converter	TE11→HE11	transf. into optimum lin. pol. hybrid mode	1.7%
corrugated up-taper	HE11	enlargement of waveguide diam. from 27.8 to 63.5 mm	≤ 0.3%
(barrier window)	HE11	(torus window)	
antenna waveguide	HE11	corrugated stainless steel w.guide for HE11 launching	< 0.1%

The losses indicated in the table were determined experimentally for the individual components in specific low-power tests. All experimental values were found to be in very good agreement with the theoretical calculations [1,2].

According to the table there are still two major contributions to the overall power loss: the content of spurious modes of the gyrotron (which can not be reconverted) and the losses of the TE01→TE11 mode converter. With respect to the first point, improvements can be expected for future gyrotrons. The most critical converter, on the other hand, has been remarkably improved by a new computer-aided design [6]. The measured losses of 2.7% essentially result from the ohmic attenuation in the transducer. Besides a further conservation of microwave power the reduction of the spurious-modes level in the most critical last section of the transmission line will be the main advantage of the new component. This novel TE01→TE11 mode transformer will be used in the transmission lines of the 70 GHz/1 MW ECRH system on the future W VII-AS stellarator.

4. Mode Measurements and Power Calibration

Fast real time power measurements in the various waveguide modes are indispensable for gyrotron tuning (with respect to maximum power at highest obtainable mode purity) and for ECRH experiments. This open problem was solved by a novel instrument ("k-spectrometer" [7]), which indicates the different modes and their direction of propagation in the form of an optical spectrum.

As an example Fig. 1 shows the wavenumber spectrum of the first three axisymmetric modes TE01 to TE03 produced in a low-power component test line. The logarithmic plot simultaneously demonstrates the high resolution of thespectrometer as well as the high quality of the inserted mode converters.

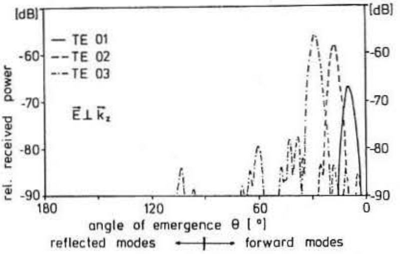


Fig.1: Spectra of TE01, TE02 and TE03 modes measured with the k-spectrometer at 70 GHz (low-power measurement).

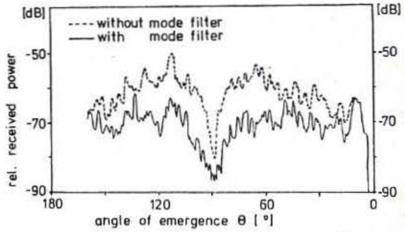
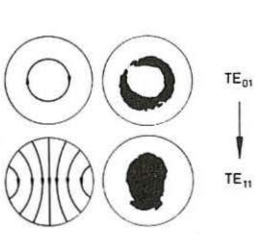


Fig.2: Multi-mode spectrum (dashed curve) of both forward and backward travelling waves produced by reflection of a TE01 wave from a crumpled aluminium foil. Attenuation of asymmetric modes by insertion of a corrugated-wall mode filter (solid curve).

Further applications of the instrument are shown in Fig. 2: Reflections of a low power TE01 wave incident on a crumpled aluminium foil in the waveguide generate a dense spectrum of forward and backward travelling waves (dashed curve). These waves – except the one in the original TE01 mode – are strongly damped after insertion of a mode selective filter as used in the high-power transmission line (solid curve). During the high power ECRH experiments a k-spectrometer was inserted in the TE01 section of the transmission line. This instrument served as a TE01 power monitor in the forward direction and allowed the optimization of the gyrotron operational parameters. A second receiver horn mounted to the spectrometer was positioned to measure reflected high order modes giving a safety switch-off signal in cases of too strong plasma reflections and/or waveguide arcing.



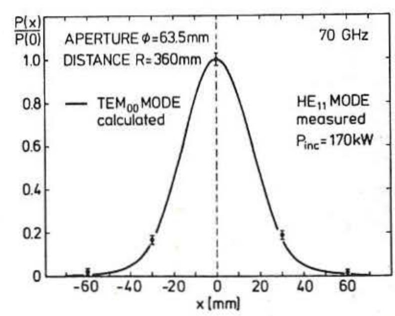


Fig.3: Thermographic burn patterns produced by the TE01 and TE11 modes which were successively generated from the TE02 gyrotron output mode (mode purity ≈ 95%) at 70 GHz (170 kW, 1ms).

Fig.4: High-power measurement (170kW) of the HE11 mode H-plane near-field pattern at 70 GHz compared with the theoretical Gaussian mode.

During high-power operation the rather pure mode composition can be deduced from burn patterns of thermographic paper. Fig. 3 shows patterns obtained after the TE02→TE01 converter and at the output of the TE01→TE11 transducer, respectively. Besides the characteristic shapes of the main modes the presence of small fractions of asymmetric modes can be seen in both cases. Measurements with the k-spektrometer and with stacked thermographic papers revealed some content (≈5%) of TE03 and TE13 modes at the gyrotron output. Nevertheless, the resulting microwave beam radiated into the torus is of high quality as verified by direct measurements inside the torus vessel. The incident power was measured by 5 pick-up antennas mounted to the inner torus wall opposite to the incoming waveguide. Fig.4 gives a comparison of experimental values with the corresponding theoretical TEM00 wave power distribution indicating the very good agreement. The measurements also show the small spread of the polarized HE11 beam at a distance of 360 mm from the aperture.

Absolute power calibration was performed using newly developed calorimetric loads [8]. In these loads an organic absorber fluid (octanol) is used, which has an appropriate power absorption length in the cm-range (compared to only 0.15 mm at 70 GHz for water). Combining this with an optimized geometry power reflections could be reduced to about −30 dB. This new absorber also allowed for the first time absorption and calibration of the concentrated HE11 output beam. In very good agreement with the previous low-power calibrations of the individual waveguide components (table in section 2) an overall efficiency of almost 90% was measured for the entire transmission system.

5. Conclusions

Safe and reliable operation of a 70 GHz ECRH system has been demonstrated in a large number of plasma discharges. The optimized high-power microwave components (tapers, bend, mode transformers, mode selective filters) allow a highly efficient mode transmission and plasma irradiation with a narrow, linearly polarized beam. The overall efficiency was almost 90%. The available power at the antenna mouth in the HE11 mode was 170 kW (at approx. 190 kW gyrotron output). Specific microwave diagnostic instruments (k-spectrometer, calorimetric loads) turned out to be indispensable tools for test purposes and ECRH experiments as well. The present 70 GHz/100 ms system is now being upgraded by another four long-pulse transmission lines, each containing two further corrugated bends with a total of approximately 3% additional conversion losses. The new system with 1 MW total microwave power is expected to have a similar efficiency as the described W VII-A transmission line due to the improvement of the efficiency of the TE01→TE11 mode converters.

References

[1] M. Thumm et al., Proc. 4th Int. Symp. Heating in Toroidal Plasmas, Rome, 1984, Vol. II, p. 1461.

[2] M. Thumm et al., Int. J. Infrared and Millimeter Waves, 6 (1985) 459.

[3] V. Erckmann et al., Proc. 12th European Conf. Plasma Physics and Nuclear Fusion, Budapest 1985, Contr. papers, Part I, p. 385.

[4] G. Müller et al., Proc. 13th SOFT, Varese, 1984, Vol. II, p. 811.

[5] H.J. Hartfuß et al., Proc. EC-5 Int. Workshop on ECE and ECRH, San Diego, 1985, in press.

[6] M. Thumm et al., Proc. EC-5 Int. Workshop on ECE and ECRH and Gyrotron User/Developer Meeting, San Diego 1985, in press.

[7] W. Kasparek and G.A. Müller, Conf. Digest 10th Int. Conf. Infrared and Millimeter Waves, Lake Buena Vista, 1985, p. 238.

[8] P.G. Schüller et al., Conf. Digest 10th Int. Conf. Infrared and Millimeter Waves, Lake Buena Vista, 1985, p. 160.