PERFORMANCE OF THE 70 GHz/ 1 MW LONG-PULSE E C R H SYSTEM ON THE ADVANCED STELLARATOR W VII-AS

W. Kasparek, G.A. Müller, P.G. Schüller, M. Thumm
Institut für Plasmaforschung, Universität Stuttgart
D-7000 Stuttgart 80, Fed. Rep. of Germany

V. Erckmann
Max-Planck-Institut für Plasmaphysik, EURATOM-Association
D-8046 Garching, Fed. Rep. of Germany

1. Introduction

Built-up and subsequent electron cyclotron resonance heating (ECRH) of net-current free plasmas (n_{eo}=1.8-5.3·10^{19} m^{-3}, T_{eo}=2.3-0.6 keV) using a single 70 GHz/200 kW/100 ms pulse gyrotron has been proven to be a powerful method to create a target plasma for neutral beam heating in the stellarator W VII-A [1]. For the new modular stellarator W VII-AS a 1 MW/70 GHz long-pulse microwave system is under construction which comprises five subsystems each designed to generate, transmit and radiate into the plasma 200 kW of millimetre-wave power with pulse length up to 3 s [2]. Low-loss power transmission from the gyrotrons to the W VII-AS device and mode transformation to achieve a linearly polarized, pencil-like microwave beam are basic requests for optimum ECRH applications. The high-power long-pulse performance of this W VII-AS ECRH system is described in the following paragraphs.

2. General Description

Each subsystem consists of a 200 kW/70 GHz gyrotron, a highly oversized circular waveguide transmission line and a quasi-optical wave launching antenna for plasma irradiation in the linearly polarized fundamental TEM00 wave mode. This Gaussian mode is ideal for the use with focusing mirrors and polarization twist reflectors. The conversion of the circular symmetric TE0n gyrotron output mode mixture (mainly TE02) to the HE11 hybrid mode, which couples with approx. 98% to the free-space Gaussian mode is performed by a sequence of highly efficient mode transducers (multi-step mode conversion: ΣTE0n → TE01 → TE11 → HE11) [3]. The intermediate TE01 wave is appropriate for weakly attenuated long-distance propagation through overmoded smooth wall circular waveguides (I.D. = 63.4 mm). The balanced HE11 hybrid mode is radiated from an open-ended, circumferentially corrugated, oversized circular waveguide (I.D. = 63.4 mm). The polarization plane can be changed by simply rotating the serpentine TE01-to-TE11 mode transformer around its axis [3]. The four transmission lines which are fed by the long-pulse gyrotrons (VARIAN VGE-8007) are mounted in two pairs at two adjacent tangential injection ports of W VII-AS and launch their microwave power from the low-field side (O-mode for fundamental or X-mode for 2nd harmonic heating). The fifth waveguide line is fed by the 100 ms pulse gyrotron (VARIAN VGE-8070) and radiates the millimetre-wave power from the high-field side (also from the outside of the torus, but with reversed magnetic field gradient, with a choice of X- or O-mode polarization) [2]. Arbitrary elliptical polarization of HE11, which is needed for current drive experiments by launching EC-waves with the wavevector at oblique angles relative to the magnetic field, is achieved by polarization converters in the TE11 mode sections [4]. The mode purity in the transmission lines is conserved by using waveguide diameter tapers with optimized non-linear profile together with circumferentially corrugated, gradual waveguide bends with varying curvature distribution and matched corrugation. The overall efficiency in the desired mode of a complete transmission line was calculated and measured (at low power levels) to be approx. 90%. At high power levels the microwave power and the mode spectrum at the outputs of the gyrotrons as well as at various positions in the transmission lines have been measured by special calorimeters and wavenumber spectrometers, respectively.

3. Microwave Generator System

Each microwave-power module contains a commercial 70 GHz/200 kW gyrotron (with complex TE01/TE02 cavity), cooling systems for the tube and the microwave window, high precision electric power supplies for the magnets, the collector voltage (80 kV) (developed by IPP Garching) and the gun anode voltage (developed by IPF Stuttgart) and a tube protection circuit [5]. Programming of the gun anode voltage allows a fast modulation (0–50 kHz) of the gyrotron microwave power for heat wave experiments in order to analyze the thermal transport of the electrons [6]. Careful control of the various gyrotron parameters (accuracy $\leqq 10^{-3}$) turned out to be the basic requirement for stable tube operation at the optimum parameter set for maximum output power and highest achievable mode purity.

The mode compositions of the four gyrotrons implemented in the system until now were analyzed in detail employing different wavenumber spectrometers [7]. The tubes exhibit a purity of the TE02 output mode between 80% and 95%. The main portion of the parasitic modes is due to the other TE0n modes (1–15% TE01, 3% TE0n ($n \geqq 3$) and 1% asymmetric modes). The higher-order TE0n modes are probably excited by the TE02 working mode in the internal collector tapers of the gyrotrons. The high TE01 mode content may additionally directly originate from the complex cavity of the tube and depends sensitively on the different operational parameters. This high TE01 mode part cannot be tolerated since the first part of the waveguide system (see chapter 4) consists of a down-taper from 63.4 mm to 27.8 mm I.D. and a gradual 90°-bend, the curvature and wall corrugations of which are optimized for a pure TE02 mode. In this bend the TE01 part of the wave would suffer strong mode conversion into highly attenuated asymmetric modes increasing the risk of rf-breakdown in the waveguide. The TE01 content is therefore reconverted to the TE02 mode in front of the TE02-bend by properly designed, phase-matched mode transducer sections [3]. The phase adjustment was performed by varying the axial position of the converter within one beat wavelength of the two modes involved. The mode composition was determined with a k-spectrometer installed after the TE02-bend and a 100% TE02-to-TE01 mode transformer. Optimum phase matching is reached if the TE02-signal is minimum. The results for the tube VGE 8007/1 (transmission line no. 2) is shown in Fig.1. The initial mode mixture (15% TE01, 81% TE02 and 4% other modes) was converted to approx. 96% TE02 and 4% other modes.

In the case of the 100 ms-pulse gyrotron an amount of 6% TE13 was measured which results from an asymmetry within the tube. A serpentine-type mode converter which exactly handles the given TE02/TE13 mode mixture to produce a pure TE02 mode was designed and is being manufactured.

4. Transmission Line System

The following table gives an overview of the basic waveguide components of the transmission line between one of the long-pulse gyrotrons and W VII-AS. All components were developed, systematically improved and manufactured by the IPF Stuttgart. The indicated typical total losses (mode conversion and ohmic losses) were determined experimentally in specific low-power tests. All experimental values were found to be in very good agreement with the theoretical calculations.

component	w.g. modes	purpose/features	total losses
down-taper	TE02/TE01	reduction of gyrotron output w.g. diameter from 63.4 to 27.8 mm	< 0.1%
mode converter	TE02/TE01	mode purification TE02/TE01→TE02	< 0.1%
corrugated bend (90°)	TE02	sinusoidal curvature, corrug. depth $0.3\cdot(\lambda/4)$, arc length 1.74 m	≦ 1.5%
mode converter	TE02→TE01	periodic radius perturbations, 8 main periods, length 0.87 m	0.4%
up-taper	TE01	enlargement of w.g. diameter from 27.8 to 63.4 mm, length 0.71 m, for long-distance transmission (30 m)	< 0.1%
down-taper	TE01	reduction of w.g. diameter from 63.4 to 27.8 mm, length 0.71 m	< 0.1%
corrugated bend (90°)	TE01	triangular curvature, corrug. depth $0.2\cdot(\lambda/4)$, arc length 2.40 m	≦ 1.5%
k-spectrometer	TE01	power and reflection monitor	< 0.2%
corrugated mode filter	TE01	attenuation of spurious TEmn ($m\neq0$)/ TMmn modes by 90-99%, length 1.2 m	≦ 1%
mode converter	TE01→TE11	periodic curvature perturbations, 8 main periods, length 2.53 m	2.7%
(polarizer	TE11	arbitrary elliptical polarization	3%)
corrugated mode converter	TE11→HE11	nonlinear variation of corrug. depth from $\lambda/2$ to $\lambda/4$, length 0.37 m	1%
corrugated bend (47°)	HE11	$\sin^2$-curvature, corrug. depth $\lambda/4$, arc length 1.50 m	≦ 1%
corrugated up-taper	HE11	enlargement of w.g. diameter from 27.8 to 63.5 mm, length 0.70 m	< 0.2%
barrier window	HE11	corrug. w.g., sapphire, FC75-cooled	≈ 1%

As result of the mode purification procedure described in chapter 3, the TE01 sections of the transmission lines (40–50 m long) including 3 tapers, 2 gradual bends and 2 mode transducers were routinely operated at full power and with a pulse length of 0.7 s without any mode filters (w.g. not pressurized). The measured mode purity at the input of the TE01-to-TE11 mode transducer is 97% (see Figs. 1 and 2) and the power losses are only 5% (10 kW). High-power long-pulse tests of the TE11/HE11 transmission line sections close to the torus are presently accomplished.

The pulse length limitation to 0.7 s is due to reflections from the compact, solid material absorbing load [2]. The low heat conductivity of the fire clay causes glowing of the material, which alters the absorption characteristics of the load. To improve the applicability to full gyrotron pulse length (3 s), modifications of the load are carried out: enlarging the volume of the absorbing material and increasing the cooling efficiency by directing the blower-driven air stream through numerous axial holes in the cylindrical fire-clay absorber.

References

[1] V. Erckmann et al., Plasma Phys. and Contr. Fusion 28 (1986) 1277.
[2] W. Kasparek et al., Proc. 14th SOFT, Avignon, 1986, Vol. 1, p. 829.
[3] M. Thumm, Int. J. Electronics 61 (1986) 1135.
[4] M. Thumm, H. Kumrić, Conf. Digest 12th Int. Conf. on Infrared and Millimeter Waves, Lake Buena Vista, 1987, p. 336.
[5] G. Müller et al., Proc. 13th SOFT, Varese, 1984, Vol. 2, p. 811.
[6] H.J. Hartfuß et al., Nucl. Fusion 26 (1986) 678.
[7] H.J. Barkley et al., Int. J. Electronics 64 (1988) 21.

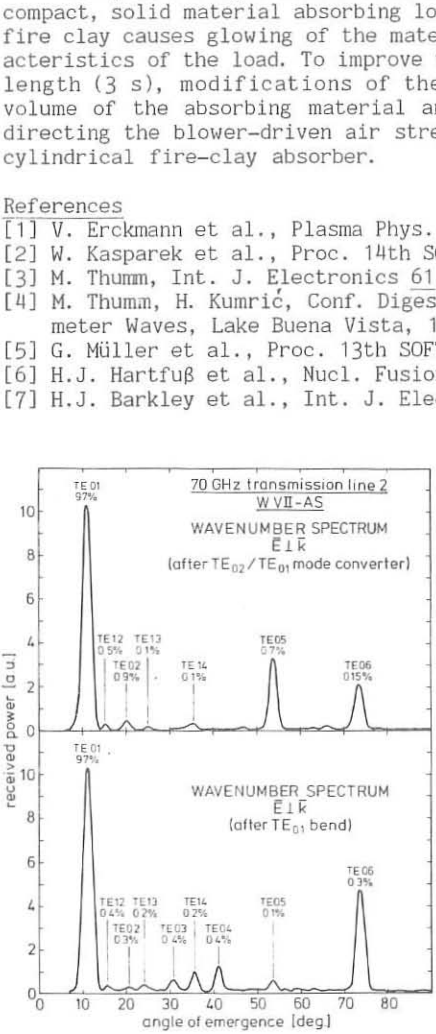

Fig. 1:
Mode spectra of TE modes measured in 70 GHz W VII-AS transmission line no. 2 at the output of the TE02-to-TE01 modes converter (upper part) and after the TE01 bend (lower part).

Fig. 2:
Thermographic burn pattern of the TE01 mode (97% mode purity) in 70 GHz W VII-AS transmission line no. 2 at the output of the TE01 bend.