PROGRESS IN THE DEVELOPMENT OF 1 MW CW GYROTRONS FOR THE STELLARATOR W7-X

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The development of high power gyrotrons in continuous wave operation has been in progress for several years in a joint collaboration between different European research centres and an industrial partner. The 140 GHz gyrotron for the W7-X stellarator operates in the $TE_{28,8}$ mode and is equipped with a highly efficient internal quasi-optical mode converter, a single-stage depressed collector and a single-disk synthetic diamond window. RF measurements were performed in short- and long-pulse operation. The first tube ("Maquette") gave an output power of more than 1 MW with an efficiency of 49% in short-pulse operation, in long-pulse operation, the pulse length was limited at about 740 kW and 100s due to an internal pressure increase. A second tube was built with improved cooling of the mirror box, an increased absorption surface (stainless steel) and a relief window for extracting the stray radiation. In short-pulse operation (12 s) an output power of 970 kW and an efficiency of 44% with single-stage depressed collector could be achieved, for a pulse length of three minutes an output power of 890 kW was measured. This limitation is due to the existing high-voltage power supply. An internal limitation was found at a reduced power of 540 kW with a pulse length of 939 s. This was caused by the pressure increase inside the tube.

Index terms – Gyrotron, single-stage depressed collector, diamond window, high-power microwaves, stray radiation, quasi-optical mode converter

Introduction

Electron-cyclotron-resonance-heating (ECRH) and electron-cyclotron-current-drive (ECCD) require gyrotrons with an output power in the Megawatt range and an efficiency of about 50%. These gyrotrons have been subject of intense investigation world-wide for a number of years. A power of 2 MW and more has been achieved in short pulse operation (few ms) and great progress has been made in the development of 1 MW long-pulse gyrotrons [1-6].

The development of gyrotrons with 1 MW output power at the Forschungszentrum Karlsruhe in collaboration with EURATOM Associations and Thales Electron Devices (TED) for continuous wave (CW) operation at 140 GHz is linked with the construction of the new superconducting Stellarator Wendelstein 7-X at the Institute of Plasma Physics (IPP) in Greifswald, Germany.

Design

The gyrotrons are equipped with a diode-type magnetron injection gun, a conventional $TE_{28,8}$ mode cavity, an advanced quasi-optical mode converter system, an output RF-window with a single edge-cooled “chemical vapour deposited (CVD)”-diamond disk and a depressed collector for energy recovery. Table 1 summarizes some - especially for long pulse operation - important parameters. Special care has been taken in order to reduce the stray radiation inside the tube as this strongly reduces the pulse length. The cavity operating in the $TE_{28,8}$ mode is equipped with roundings between the cylindrical and the tapered parts and this leads to a mode purity of 99.9% at the cavity output. The launcher uses a deformed cylindrical waveguide section (prebunching section) to convert the main mode into a mixture of modes such that 98% of the power is contained in a bundle with a Gaussian-like amplitude profile. The radius is slightly uptapered in order to reduce the Q factor of the section between the cavity and the helical cut and suppresses spurious oscillations generated by the spent

Cavity mode	$TE_{28,8}$
Accelerating voltage	81 kV
Beam current	40 A
Depression voltage	< 35 kV
Cavity magnetic field	5.56 T
Overall efficiency for TEM_{OO}	>45 %
Frequency (temperature stabilized)	139.8 GHz
RF-beam radius at window	23.3 mm
RF-beam radius in waist	22 mm
Location of waist (distance from window outside gyrotron)	250 mm
Mode purity at resonator output	99.9 %
Launcher efficiency	~98%
Stray radiation	~ 2 %
Launcher taper angle	0.004 rad
Perturbation amplitude	0.041 mm

Table 1: Design parameters

electron beam of the gyrotron in the launcher section. The amplitude of the wall perturbation is 0.041mm as well for the azimuthal as for the longitudinal bunching, the perturbation however for azimuthal bunching is shifted by 17 mm towards the output with respect to the perturbation for longitudinal bunching. All these steps lead theoretically to an efficiency of about 98%, and a stray radiation level of only 2% [7,8]. The power distribution on the (unrolled) launcher wall is shown in Fig. 2. The white line of the left figure indicates the contour of the helical cut which is placed at a very low field amplitude. The view on the right shows the distribution of the radiated wave bundle.

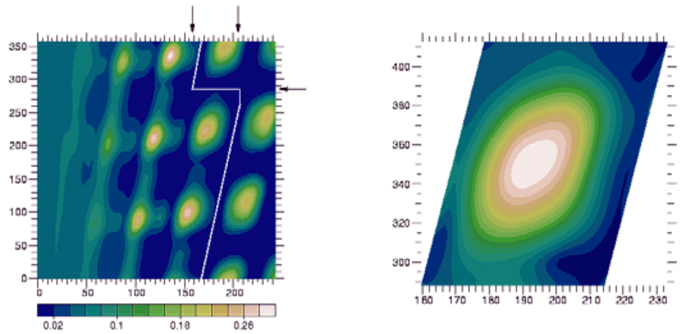

Fig. 2: Power distribution on the launcher wall

For continuously operated gyrotrons with output levels in the megawatt region it is essential to have a chemical vapour deposited (CVD) diamond window (at least if one does not like very complicated constructions for the window design or complicated RF-field distributions). RF-grade diamond discs feature low loss tangent values ($\sim 2 \cdot 10^{-5}$) at room temperature and 140 GHz, high thermal conductivity which exceeds those values of copper, very low expansion and high mechanical strength [9].

Single-stage depressed collector operation not only increases strongly the efficiency to about 50%, it is also needed in order to decrease the power densities on the collector surface to values which can be handled technically.

Results

The first tube yielded an output power exceeding 1 MW at an efficiency of 49% in short-pulse operation; it suffered however by the pressure increase inside the tube even at only 740 kW output power (efficiency: 32.5% with depressed collector). The pulse length was limited to 100s. A second tube, the prototype tube, was constructed with a few very important modifications: the stainless steel surface was increased in order to have a greater surface for RF absorption inside the tube, a relief window for the stray radiation was installed and the cooling of

Fig. 3: View of the prototype tube

the mirror box was strongly improved. The modifications can be seen in Fig. 3. Apart from this, the window was given a tilt of 1.5° in order to avoid the reflected power – if any – going back into the cavity and reducing the generated power [10].

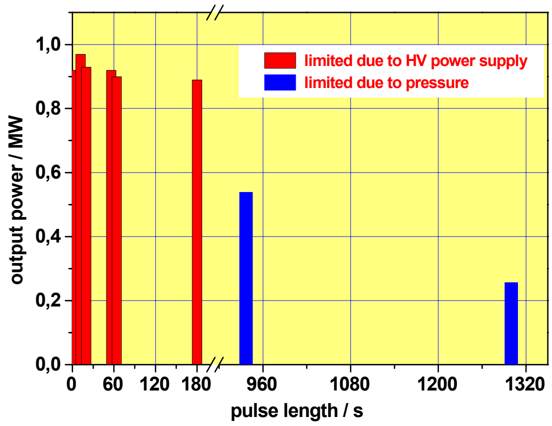

Fig. 4: Output power for different pulse lengths

Fig. 4 shows the result obtained during long- pulse operation. For a pulse-length of 11.7s an output power of 970 kW and for three minutes an output power of 890 kW has been achieved. The efficiencies were measured to be 44 and 42%, respectively. At these output power levels, the pulse lengths are limited due to the HV power supply at Forschungszentrum Karlsruhe. At reduced beam currents down to 30A, continuous operation is possible. The limitation of 939 s at a power level of 540 kW, and also of 1300 s at 250 kW, is given due to the pressure increase inside the tube.

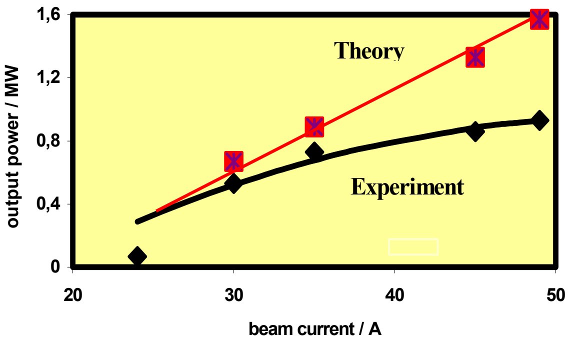

Fig. 5: Output power as function of beam current

With these results, the specification of an output power of 1 MW in long pulse operation (30 min) was almost achieved. Unfortunately the output power did not increase strongly at higher beam current. This behaviour is seen in Fig. 5 where the output power is plotted for different beam currents. During this measurement, only the voltage has been optimised with respect to high output power at a fixed magnetic field. The magnetic field, however, has not been optimised for short pulse operation. Theoretically, an almost linear dependence was calculated, but the measurements show a saturation effect for currents between 40 to 50 A. It is assumed that due to a non-homogeneous distribution of the electron emission from the emitter surface the quality of the electron beam is deteriorated strongly in a way that the generation of the RF-power is strongly reduced [11]. Evidence for this effect was given by a visual inspection of the emitter after the measurements with a scanning electron microscope by which clearly areas with different porosity and different Barium layers could be seen. For the next tube, a better quality assurance especially with respect to the electron emitter will be performed by microscope views of the surface.

The pressure increase in the gyrotron tube was measured to follow an exponential dependence with time. After a 15 minutes pulse, for which the gyrotron was switched off due to the pressure increase, the temperature of the internal ion getter pumps was determined by measurements with an infrared camera through the transparent diamond window. A temperature of 250°C was measured. However, assuming this to be the temperature distribution on the surface, the strong gradients cannot be understood. It is assumed that the temperature of interior parts of the ion getter pumps is seen through the copper grid which protects the RF penetrating into the pump. This grid reduces the radiated intensity and thus shows a lower temperature than according to the measured values. So we assume that firstly the temperature of internal parts of the ion getter pumps is seen and secondly the temperature is even higher than the measured values. These internal parts of the ion getter pumps are isolated (high voltage of 5 kV) so it seems rather difficult to improve the cooling of these parts (HV feed through). On the other hand, a complete shielding of the pump from the RF is difficult again due to the HV connection. Either one has to decrease the stray radiation or put the ion getter pumps outside the gyrotron. In this case, the RF-leaking HV-connection would not be affected by the stray radiation.

	922 kW; 55 s		892 kW; 180 s	
	Efficiency	42.2%	Efficiency	42.2%
	Power / kW	Power/ %	Power / kW	Power / %
Generated Power	972±48	100	941±47	100
Ohmic Losses	37±5	3.8	37±5	4.0
Int. Stray Rad.	**13±4**	**1.3**	**12±4**	**1.2**
Window Losses	0.4	0.04	0.4	0.04
Output Power	922±46	95.2	892±45	95.0
Ext. Stray Rad.	**16±4**	**1.7**	**16±4**	**1.6**
Directed Power	907±45	93.5	876±44	93.3

Table 2: Power balance of the prototype W7-X gyrotron

Table 2 shows the power calorimetrically measured consumption of different components for two pulses. The relative values refer to the generated power and are almost the same.

The amount of internal and external stray radiation add to about 2.8% to 3% (with an error of 0.6%). This value agrees very well with the theoretical value of 2%, and taking also into account the fabrication tolerances, a better value hardly can be achieved. The improvement for the next gyrotron are that the ion getter pumps will be placed outside the gyrotron with an RF-shielding grid between mirror box and pump.

Knowing the reason for the limitation of the tube, the development phase for the gyrotrons has been finished and seven series gyrotrons have been ordered. Including the existing ones (two from TED and one from CPI), a total number of ten gyrotrons will be installed.

Conclusions

The development for continuously operated 140 GHz gyrotrons at an output power level of 1 MW was very successful, though the specified values were not completely achieved. The reasons are known. The limitation of output power is seen in the azimuthal inhomogeneity of the electron beam, the limitation of the pulse length is due to a temperature increase of internal parts of the ion getter pumps. To avoid these effects, first a better cathode quality assurance is necessary and second the ion getter pumps are placed outside the gyrotrons.

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