Recent Results of the 1-MW, 140 GHz, CW Gyrotrons for the Stellarator W7-X

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Abstract. The first series tube of the gyrotrons for W7-X was tested at the Forschungszentrum Karlsruhe and yielded a total output power of 980 kW with an efficiency of 31% (without SDC) in short pulse operation and of 920 kW in pulses of 180 s (efficiency of 45% at depression voltage of 29 kV). The directed output power was 906 kW. The pulse length at full power (1 MW) is limited at Forschungszentrum Karlsruhe by the available power supply. At reduced electron beam current, it is possible to operate at longer pulse lengths. At an output power of 570 kW (electron beam current of 29 A), the pulse length was increased to 1893s. There was no physical reason for a limitation of this pulse: the pressure increase during the pulse was less than a factor of two and ended up at a very low value in the 10^{-9} mbar range. The tube was delivered to IPP Greifswald for tests at full power and up to 30 minutes pulse length. The output power yielded 920 kW as at Forschungszentrum. Again, no indications for a limitation in pulse length was found. The 2nd series tube has been tested in short pulse operation and showed a strange behaviour concerning mode hopping which has not yet been understood.

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INTRODUCTION

High plasma temperatures are needed for initiating nuclear fusion reactions in magnetically confined fusion plasmas. One possibility for heating the plasma to the necessary temperatures is the injection of millimeter waves with a frequency corresponding to the cyclotron motion of the electrons in the confining magnetic field.

Gyrotron oscillators have proven to be highly efficient sources of coherent millimeter wave radiation at the interesting frequencies between 110 and 170 GHz. They have been used successfully for electron cyclotron resonance heating (ECRH) and electron cyclotron current drive (ECCD) experiments [1] which have been proven to be important tools for plasma devices especially for stellarators as they provide both net current free plasma start up from the neutral gas and efficient heating and current drive in the plasma.

The application of ECRH is limited due to the lack of powerful sources operating at an appropriate frequency. The major problems of high power, high frequency long-pulse gyrotron oscillators were caused by the dielectric output windows, by the power capability of the collector and by the stray radiation absorbed inside the gyrotron.

The development of gyrotrons with an output power in the megawatt range has been subject of investigation worldwide for a number of years. Microwave powers of 2 MW and more have been achieved in short-pulse operation and great progress has been made in the development of 1-MW long pulse gyrotrons during the last few years.

GYROTRONS-DESIGN

The RF-cavity operates in the $TE_{28,8}$ mode. It is a standard cylindrical cavity with a linear input taper and a non-linear output taper. Special care has been taken for the design of the quasi-optical mode converter [2] to generate only a very little amount of stray radiation. The radius of the antenna waveguide launcher is slightly uptapered towards the output by an angle of 4 mrad in order to avoid parasitic oscillations in this region. Due to the low fields along the edge of the helical cut, this advanced dimpled-wall launcher generates a well focused Gaussian-like field pattern with low diffraction. In combination with a three mirror system the desired Gaussian output beam pattern can be obtained. The output vacuum window [3] uses a single edge-cooled disk of chemical vapor deposited diamond (CVD-diamond) with an outer diameter of 106 mm, a thickness of 1.8 mm (four half wavelengths) and a window aperture of 88 mm.

TABLE 1. Design Values.

RF output power	1 MW
Accelerating voltage	81 kV
Beam current	40 A
Cavity mode	$TE_{28,8}$
Efficiency	45 %
Cavity radius	20.48 mm
Self consistent quality factor	1100
Cavity magnetic field	5.56 T
Launcher taper	4 mrad
Launcher efficiency	98 %
Window aperture	88 mm

EXPERIMENTAL RESULTS OF 1st SERIES TUBE: SHORT-PULSE OPERATION

With the prototype, two problems were faced. The specified output power of 1 MW has not completely achieved and the pulse length was limited to about 15 minutes even at reduced power of 534 kW [4,5].

To eliminate the limitation in output power for the series tubes, a better quality assurance of the emitter ring has to be performed before installing it into the gyrotron. To avoid the pulse length limitation it was decided to use external ion getter pumps with better shielding against RF stray radiation.

Knowing the reasons for the limitation in power and pulse length, the development phase for the gyrotrons was finished and seven series tubes were ordered. The first series tube had been delivered to FZK and tested in short and long pulse operation.

The output power of the series tube versus beam current at constant magnetic field showed an almost linear. The saturation in power as seen in the prototype could not be found indicating the good emission of the cathode. An output power of 1 MW at 40 A and 1.15 MW at 50 A was measured in short pulse operation (ms). The corresponding efficiencies without depressed collector were 31 % and 30%, respectively.

RF-field distribution measurements (perpendicular to the output RF-beam direction) were performed at different positions with respect to the window (Figure 1). The Gaussian content was calculated to be 97.5 %.

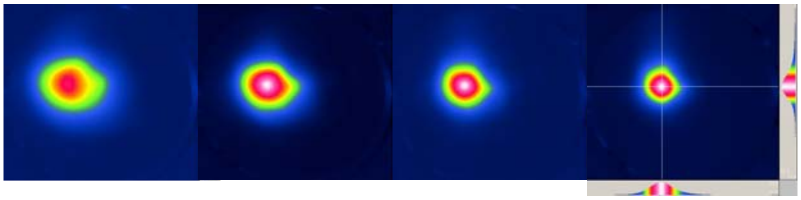


FIGURE 1. Beam reconstruction: Shown are the power distributions at different distances from the window (from the left: 1282 mm, 1082 mm, 882 mm and 682 mm).

EXPERIMENTAL RESULTS OF 1st SERIES TUBE: LONG-PULSE OPERATION

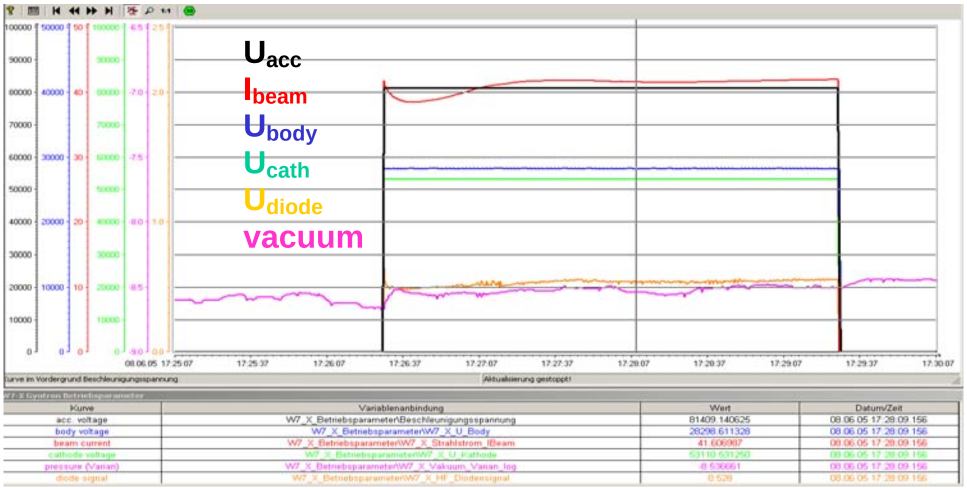
The optimisation procedure for finding the operating parameters at high output power in long pulse operation was performed in 1s-pulses assuming that the instantaneous power is well described by the frequency difference between the initial frequency and the instantaneous frequency (after one second). In a range between 5.52 –5.56 T of the magnetic field at the cavity, no maximum for the output power was found. The power increased slightly with increasing magnetic field. In order to achieve the maximum output power, the accelerating voltage (this corresponds to the energy of the electrons inside the cavity) was adjusted and followed nicely the law that the ratio between magnetic field and the relativistic factor γ has to be constant. Increasing the voltage beyond this value leads to an excitation of neighbouring modes. The measurements were performed at a constant beam current of 40 A, but with optimising the electron beam radius inside the cavity.

A strong dependence of the output power has been found for different electron beam radii inside the cavity. The desired mode can only be excited in a narrow range between 10.25 mm and 10.43 mm. At lower beam radii, arcing occurs, at higher radii a wrong mode (or the counter-rotating $TE_{28,8}$ mode) is excited. The optimum value of the beam radius decreases slightly with decreasing cavity field and beam current.

In long pulse operation, the power was measured calorimetrically by the temperature increase of the cooling water of the RF-load. This load is placed about 6m away from the gyrotron window. The RF beam is focused and directed by two matching mirrors into the load. In order to reduce the power loading on the surface, a set of polarizers is installed to produce a circularly polarized beam. The first matching mirror owns a corrugated surface. A small amount of the RF beam is coupled out and focused on a horn antenna with a diode detector to get a signal proportional to the output power. This signal, however, is not used for power measurements as the calibration is complicated and can vary easily.

In long pulse operation, the gyrotron was operated with depressed collector. The electrons are decelerated after the RF interaction by a positive bode voltage U_{body} which usually is chosen to a value between 25 and 30 kV. The collector is at ground potential.

Fig. 2 displays the gyrotron operating parameters for a pulse length of three minutes. Shown are the electron beam current I_{beam}, the body voltage U_{body} (decelerating voltage between cavity and collector), the accelerating voltage U_{acc} (voltage between cavity and electron emitter corresponding to the energy of electrons in the cavity), the diode signal U_{diode} (a relative measure for the output power) and the pressure inside the tube measured as the current of the ion getter pumps. It is increasing very smoothly. The increase of pressure is less than a factor of two ending up in the 10^{-9} mbar range.



Kurve im Vordergrund Beschleunigungsspannung

Aktualisierung gestoppt!

W7-X Gyotron Betriebsparameter

Kurve	Variablenanbindung	Wert	Datum/Zeit
acc. voltage	W7_X_Betriebsparameter\Beschleunigungsspannung	81409.140625	08.06.05 17:28:09.156
body voltage	W7_X_Betriebsparameter\W7_X_U_Body	28298.611328	08.06.05 17:28:09.156
beam current	W7_X_Betriebsparameter\W7_X_Strahlstrom_IBeam	41.606987	08.06.05 17:28:09.156
cathode voltage	W7_X_Betriebsparameter\W7_X_U_Kathode	53110.531250	08.06.05 17:28:09.156
pressure (Varian)	W7_X_Betriebsparameter\W7_X_Vakuum_Varian_log	-8.536661	08.06.05 17:28:09.156
diode signal	W7_X_Betriebsparameter\W7_X_HF_Diodensignal	0.528	08.06.05 17:28:09.156

FIGURE 2. Gyrotron operation parameter for the 1893 s, 540 kW pulse. (From top to bottom: accelerating voltage, beam current, body voltage, cathode voltage, diode signal and pressure).

The highest output power inside the load for a three minute pulse was measured to 905 kW. Including the external stray radiation determined by the calorimetric measurement performed inside the microwave chamber, the total power was 920 kW with an efficiency of 45%. The directed power was measured to 906 kW and thus the specified value of 900 kW for the Gaussian content has been achieved.

At Forschungszentrum Karlsruhe, the available HV power supply is only able to operate up to three minutes at full power, but at reduced electron beam current at less than 30 A longer pulses can be achieved. Figure 2 shows the operating parameters for a pulse of about 31 minutes (1893 s) with an output power of 540 kW. It can be seen by the diode signal that the output power is very stable. The scale for the pressure is logarithmic with a factor of 1.8 per division. The pressure increase is lower than a factor of 2 ending up at about $6 \cdot 10^{-9}$ mbar.

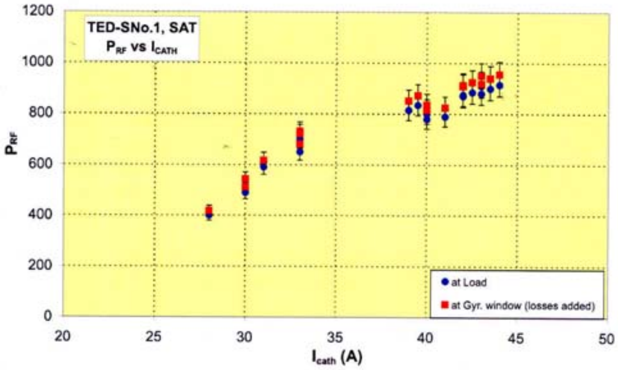


Figure 3. Output power and power to load (in a distance of about 25 m) for different beam currents.

After the successful tests at the Forschungszentrum Karlsruhe, the tube was delivered to IPP Greifswald for tests at highest output power and a pulse length of 30 minutes. A directed output power of 870 kW was measured inside the load after a 25 m long transmission line with 7 quasi-optical mirrors, and a total output power of about 910 kW was estimated taking the losses in the transmission line into account (world record in energy content). Figure 3 shows the output power and directed power (without external stray radiation) for some shots at high power level and pulse lengths up to 30 minutes.

EXPERIMENTAL RESULTS OF 2nd SERIES TUBE: SHORT-PULSE OPERATION

Even for short pulse operation, the behaviour of the 2nd series gyrotron was found to be completely different from the 1st series tube. At a pulse length of 1 ms, the output power was 1.2 MW at a beam current of 50 A (Figure 5) which is comparable to the output power of the 1st series tube. However, it was not possible to increase the pulse length without mode hopping (or mode mixing) to the $TE_{22,7}$ mode at about 137 GHz. As the power is reduced for this mode, of course also the total power (averaged over the hole pulse length) is reduced. Figure 4 gives the RF pulse length for the desired mode ($TE_{22,8}$-mode) as function of different accelerating voltages. Even at rather small accelerating voltages of 74 kV the pulse length for the desired mode is limited to about 4 ms. Figure 5 shows the drop in output power for a pulse length of 1 ms and of 3 ms when the accelerating voltage exceeds 81 kV. The voltage depression between cathode and cavity was calculated to be about 5 kV. As even for very low accelerating voltages mode hopping takes place this cannot be caused by the increase of the electron energy inside the cavity due to charge neutralisation. of the tube. The reason for this effect is not yet understood.

It was tried to operate the gyrotron even in long pulse operation of 1s, however, no parameters for stable operation could be found.

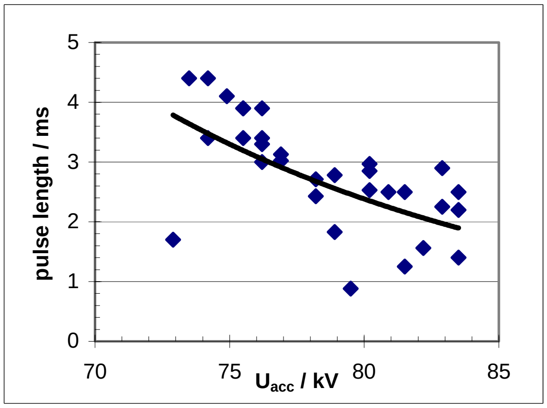


Figure 4. Pulse length of the desired TE22,8-mode. After the given time, mode hopping takes place. (The solid line shows an exponential fit.)

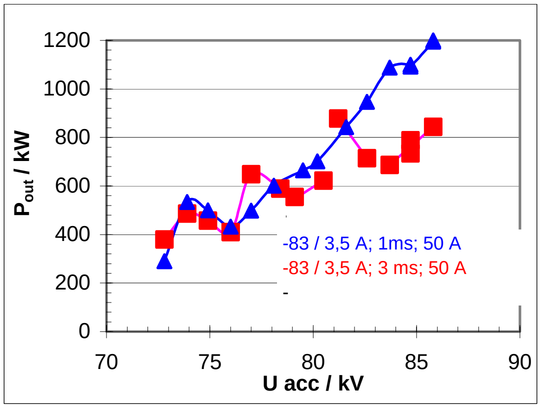


Figure 5. Output power as function of the accelerating voltage. The power is integrated over one shot of 1 ms (triangles) and 3 ms (rectangles).

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