Experimental Results of the 1-MW, 140-GHz, CW Gyrotron for W7-X

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Abstract. A 10 MW ECRH system will be provided by FZK in collaboration with several European associations for the stellarator W7-X. The RF power will be delivered by 10 gyrotrons operating at 140 GHz in CW with 1 MW each. The development of this gyrotron has been performed within a European collaboration in an industrial frame. Two R&D tubes have been built, up to know one serial tube has been passed the acceptance tests. The design of the gyrotron will be described and short pulse and long pulse results of the first serial gyrotron will be discussed. This gyrotron has been successfully operated at more then 900 kW with a pulse length of 30 min.

1. Introduction

High power, high frequency gyrotrons are widely used in the field of fusion research with magnetically confined plasmas. Due to the very localised absorption of the RF power, based on the electron cyclotron resonance mechanism, gyrotrons are an ideal tool for heating (ECRH), current drive (ECCD) and suppression of instabilities in plasmas. They also can provide a current free plasma start up from the neutral gas and noninductive CD. The increasing size of existing and planned fusion devices asks for gyrotrons with an output power of 1 MW (or even more) in continuous wave (cw) operation in the frequency range 110 – 170 GHZ to be technically feasible and still economically compeditive with other heating methods.

The stellarator W7-X will require a 10 MW electron cyclotron wave (ECW) system [1] which will be provided by FZK. A European collaboration has been established to develop and built in an industrial frame, together with Thales Electron Devices (TED), gyrotrons which operate at 140 GHz with 1 MW output power in continuous wave.

Outstanding features of this development are:

- A high mode purity of the output beam which is achieved by the use of an advanced quasi-optical launcher and mirror system.
- The output window is made of chemical vapor deposited diamond (CVD diamond) with low RF losses, very high thermal conductivity and excellent mechanical properties.

- Increase of the overall efficiency and reduction of the thermal loading of the collector of these tubes by means of a single stage depressed collector.

2. Design of the gyrotron

A DC heated magnetron injection gun which works in the temperature limited region is used. It is designed as a diode type gun (without intermediate anode) and operates at an accelerating voltage of 80 kV creating a beam current of 40 A with a current density at the emitter of 2.5 A/cm^2. The average velocity ratio of the electrons ($v_\perp/v_\|$) is 1.3 with a spread of 1.2. Special care has been taken with respect to the length and wall coverage of the gun – cavity region. This section is equipped with copper and absorbing ceramic rings in order to avoid spurious oscillations which could degrade the beam quality.

The cavity is a standard cylindrical design with lengths and angles as given in Table I and optimized for the mode $TE_{28,8}$. The transitions between the sections have been equipped with roundings which reduces the conversion to unwanted modes. Thus a mode purity at the output taper of 99.9 % has been achieved. The beam is placed at the first radial maximum of the electrical field of the $TE_{28,8}$ mode to ensure a strong interaction of the electrons with the design mode. The compression ratio (B_{cavity}/B_{gun}) of the beam is 23.5.

The launcher and quasi-optical system are optimised to convert the rotating $TE_{28,8}$ cavity mode into a fundamental Gaussian beam with an efficiency of 98 % [2,3]. Main features are a dimpled-wall waveguide launcher, one quasi-elliptical mirror and two toroidal mirrors. The waveguide launcher is tapered with a 4 mrad angle to complicate the possible excitation of spurious modes.

The output vacuum window is a single, edge-cooled CVD diamond disk with an inner apperture of 88 mm mounted almost perpendicular to the output beam. To minimise reflections at the window a resonant thickness for 140 GHz has been choosen (two wavelengths inside material). Due to the low loss tangent of diamond the absorbed power of a 1 MW beam is only 705 W, the very high thermal conductivity limits the central temperature increase in cw operation to about 60 °C. The radius of the mm wave beam at the window is 23.3 mm, the waist radius is 22 mm, located at 250 mm after the window.

The isolation of the collector from the cavity region allows the application of a decelerating voltage. This measure reduces the residual energy of the spent

Frequency	140 GHz
Cavity Mode	$TE_{28,8}$
Output power	1 MW
Pulse Length	1800 s
Accelerating voltage	81 kV
Beam current	40 A
Velocity ratio α	1.3
Cavity magnetic field B_c	5.56 T
Gun magnetic fiel B_g	0.237 T
Beam radius in the cavity R_b	10.1 mm
Space charge depression	5.7 kV
Taper angles of cavity	2.5/0.0/3.0 deg
Lengths of the cavity sections	16.5/14.5/15.0 mm
Cavity radius	20.48 mm
Peak cavity wall loading P_{peak}	2 kW/cm^2
Electronic efficiency	35 %
Overall efficiency	48 %
Window material	CVD diamond
Window diameter outer/inner	106/88 mm
Window thickness	1.8 mm
Absorbed Power in window	705 W
Gaussian output	98 %
RF beam waist radius w_0	22.0 mm
Collector diameter/length	450/1300 mm

Table I: Main characteristics of the 140 GHz

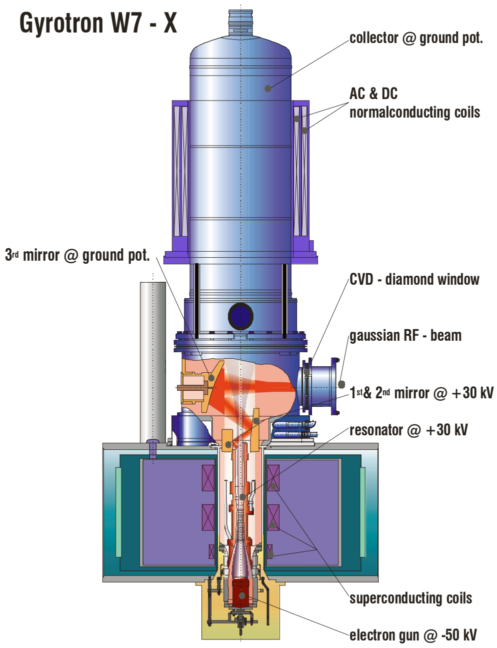

Figure 1: The gyrotron installed in the magnet.

electrons and lowers the thermal load of the collector resulting in a higher overall efficiency. During operation the collector is at ground potential, the cathode voltage is set to -54 kV and the cavity voltage to +27 kV. To equalise the the thermal loading of the collector, watercooled solenoidal coils sweep the electron beam across the surface in axial direction with a repetition frequency of 7 Hz. An advanced sweeping system using transverse fields has the advantage of a further reduction of the peak wall loading. This system is presently under investigation [4]. A picture of the tube installed in the magnet is given in Figure 1.

3. Experimental results

Here we will discuss experiments with the series tubes, results from two R&D tubes have been reported in [5].

The first series tube has 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 dependance. A saturation in power as seen in the R&D tubes could not be found, indicating the uniform 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 (see Figure 2).

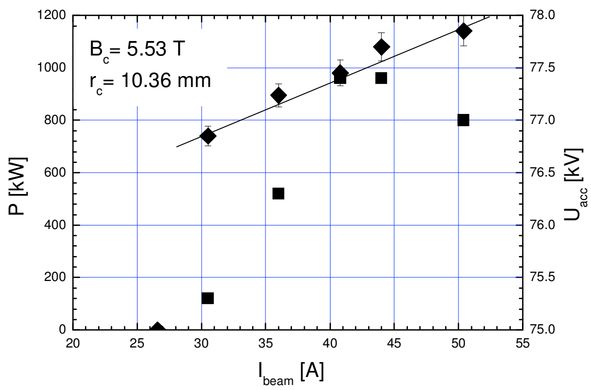

Figure 2: Dependance of output power (diamonds) at optimised accelerating voltage (squares) of beam current for fixed beam radius

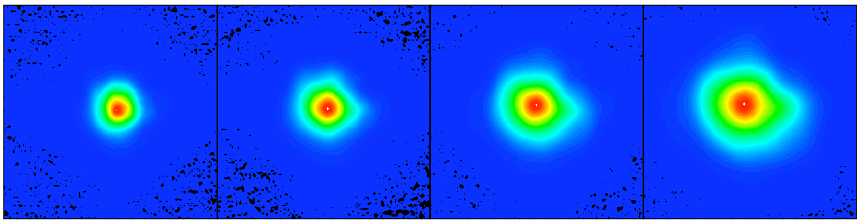

Figure 3: Thermograhic image of the output beam. Shown are the power distributions at different distances from the window on a target with the dimensions 167x167 mm (from left: 474 mm, 674 mm, 874 mm and 1074 mm).

Thermographic images of the RF-field distribution were taken at several planes perpendicular to the output RF-beam direction (see Figure 3). From these measurements at different positions with respect to the window the complex field distribution can be reconstructed and the parameters of a fundamental Gaussian beam can be determined. The Gaussian content of the output beam was calculated to be 97.5 %.

The optimisation procedure for finding the operating parameters at high output power in long pulse operation was performed in 1 s-pulses assuming that the instantaneous power is well described by the frequency difference between the initial frequency and the instantaneous frequency after one second. As an example Figure 4 shows the variation of the frequency with time in a 570 kW pulse. In that case the frequency drop is about 160 MHz and stays nearly constant after about 0.6 s, indicating a thermal equilibrium of the cavity.

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 (corresponding to the energy of the electrons inside the cavity) was optimised (see Figure 5). Increasing the voltage beyond this value leads to an excitation of neighbouring modes.

A strong dependence of the output power has been found for different electron beam radii inside the cavity. As shown in Figure 6, 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.

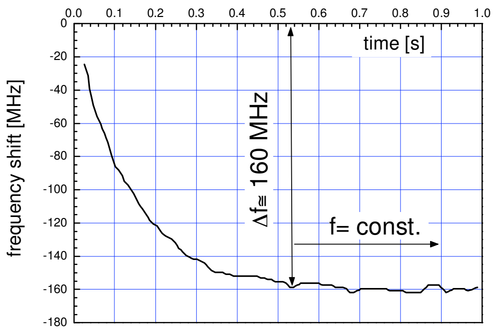

Figure 4: Time dependance of the gyrotron frequency.

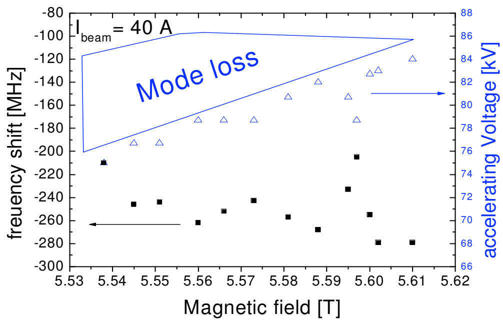

Figure 5: Frequency shift and optimised accelerating voltage for different magnetic fields in the cavity.

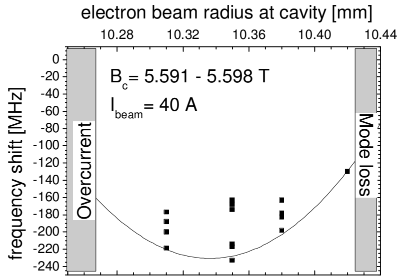

Figure 6: Optimisation of electron beam radius in the cavity.

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 6 m away from the gyrotron window (see Figure 7). The RF beam is transmitted to the load with a quasi optical transmission line following the design principles which are also used for W7-X transmission system [6]. The beam is focused and directed by two matching mirrors into the load. The first matching mirror incorporates a grating 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. In order to equalise the power loading on the surface of the load, a set of two polarizers is installed to produce a circularly polarized beam.

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

Figure 8 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 which is an improvement compared to the R&D tubes.

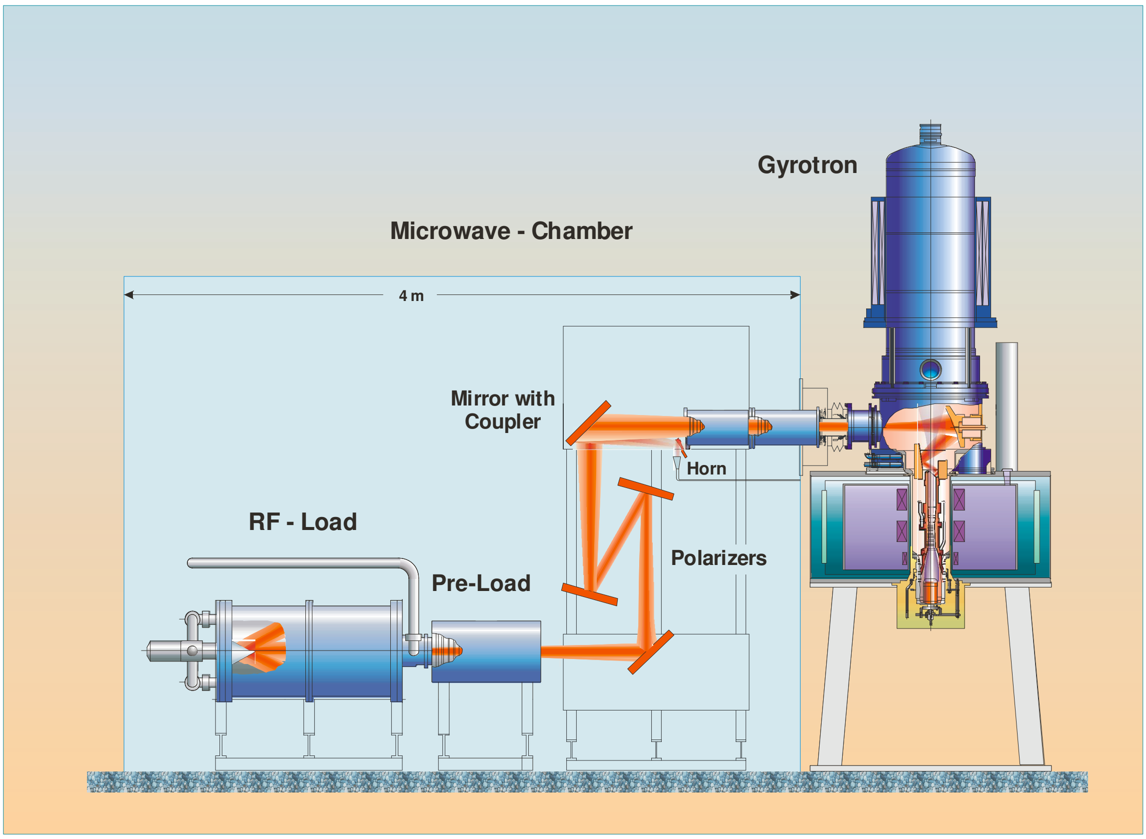

Figure 7: Experimental arrangement for long pulse tests at FZK

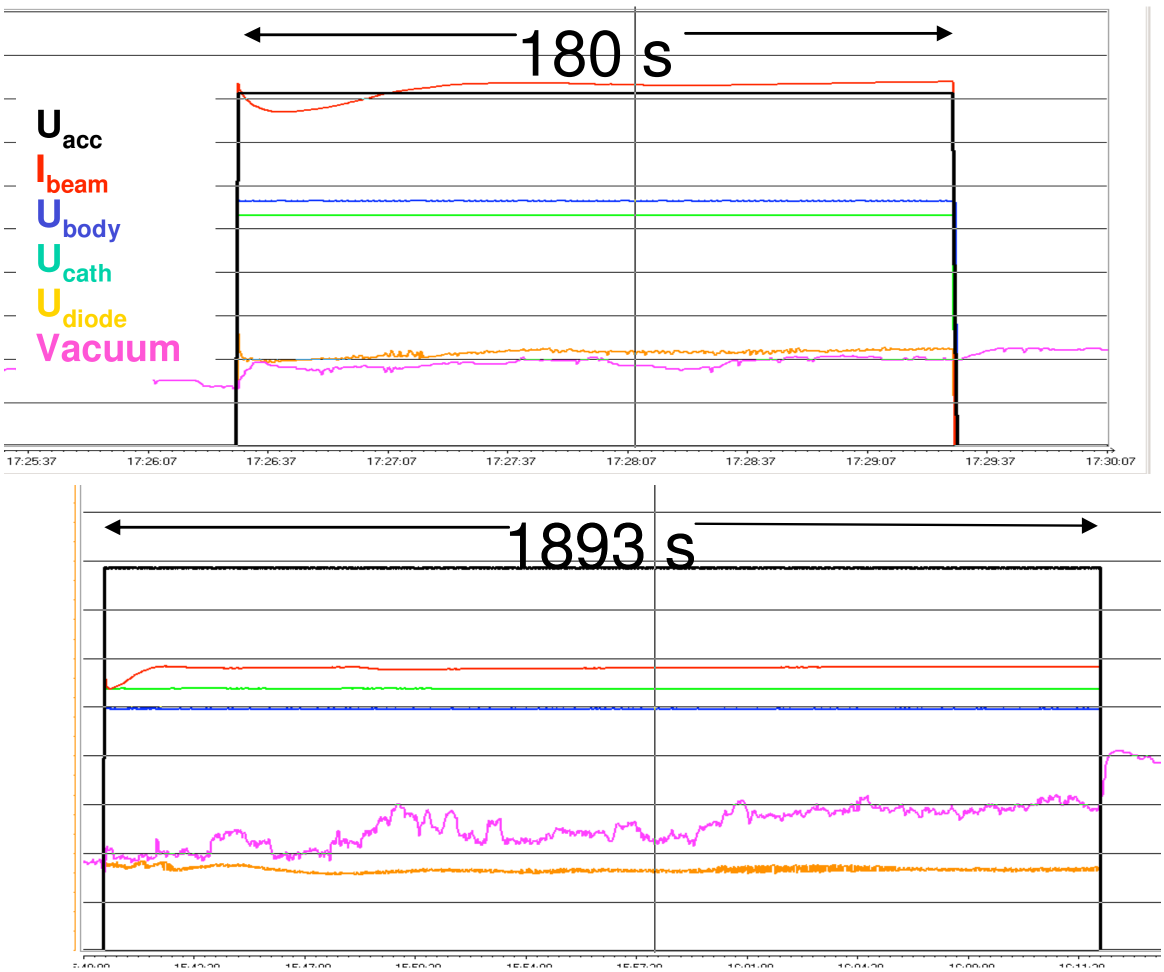

Figure 8: Operating parameter for a pulse length of three minutes (top) with an output power of 920 kW and a long pulse of 1893 s (bottom) with an output power of 604 kW at reduced beam current.

The highest directed power inside the load for a three minute pulse was measured at 906 kW. Including the external stray radiation determined by calorimetric measurements performed inside the microwave chamber, the total gyrotron output power was 920 kW with an efficiency of 45 %. 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. However, at reduced beam current the pulse length can be increased up to 30 minutes. An example of a 1893 s pulse with reduced beam current and an output power of 570 kW is given in Figure 8. It shows a nearly constant behaviour of the pressure in the tube.

After the successful tests at the Forschungszentrum Karlsruhe, the tube was sent to IPP Greifswald for tests at highest output power and a pulse length of 30 minutes. There, a directed output power of 870 kW was measured inside the load after a 25 m long quasi-optical transmission line with 7 mirrors, and a total output power of about 910 kW was estimated taking the losses in the transmission line into account (energy content = 1.64 GJ). Figure 9

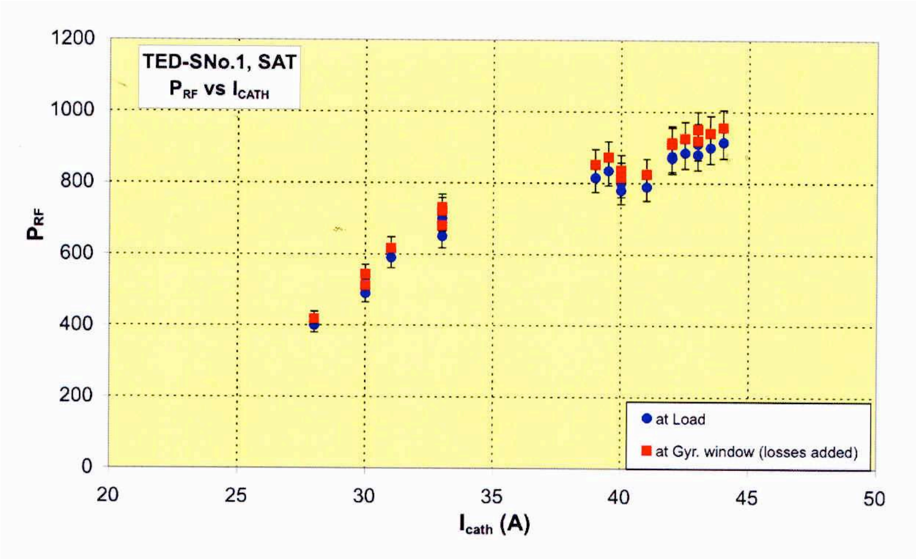

Figure 9: Output power and power to load (at a distance of about 25 m) for different beam currents achieved in long pulse operation (typically 5 min) at IPP Greifswald.

shows the output power of the gyrotron measured at the load and the total output power at the window during the conditioning of the system at a typical pulse length of 5 minutes.

3. Conclusions

The first serial gyrotron for the stellarator W7-X has fullfilled the specifications with respect to output power, efficiency, pulse length and mode purity. It showed an improved performance compared to the R&D gyrotrons. In short pulse operation the power was measured to be 1 MW, at extended operation up to 30 minutes the power was 922 kW at an efficiency of 45 %.
The serial tube No. 2 has failed to meet the specifications at FZK, the serial tube No. 3 is currently being installed at IPP and will undergo acceptance tests.

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