Development of multi-megawatt gyrotrons at Forschungszentrum Karlsruhe

B. Piosczyk, G. Dammertz, R. Heidinger, K. Koppenburg, M. Thumm

Abstract—Within the European Community the development of high power gyrotrons in continuous wave (CW) operation is in progress since several years in a joint collaboration between research centers with an industrial partner. In particular, the development of a 1 MW, CW, 140 GHz gyrotron for use at the stellarator Wendelstein 7-X has been successfully finished. A first series has already been delivered and tested. With that tube, an output power of 1000 kW has been achieved in short pulse operation (ms) at an electron beam current of 40 A. For a pulse length of 3 minutes, limited by the available high-voltage (HV) power supply, an output power of 920 kW has been obtained at the same current. At a reduced beam current of 29 A an output power of 570 kW was measured with a pulse length of 1893 s without significant increase of the tube pressure.

For application at ITER the development of a 2 MW, CW, 170 GHz coaxial cavity gyrotrons started within an European cooperation. In parallel to the design and manufacturing of a first industrial prototype tube, a short pulse pre-prototype tube has been operated, in order to verify the design of critical components under realistic conditions. Another task at Forschungszentrum Karlsruhe (FZK) is the development of frequency step tunable gyrotrons operating in the range from 105-140 GHz. Such gyrotrons would offer some advantage in the use of microwave sources for stabilization of current driven plasma instabilities in fusion plasma devices (neoclassical tearing modes: NTM).

Index Terms—Gyrotron, coaxial gyrotron, step tunability, frequency tuning, single-stage depressed collector, diamond window, high-power microwaves, stray radiation, quasi-optical mode converter

I. INTRODUCTION

Gyrotron oscillators have proven to be highly efficient sources of coherent millimeter wave radiation in the frequency range above 100 GHz. They have been used successfully for plasma heating (electron cyclotron resonance heating, ECRH), and current drive experiments (electron cyclotron current drive, ECCD) as well as for controlling of NTM instabilities [1]. In addition gyrotrons can be used for plasma start up from the neutral gas.

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 years [2]–[8].

Under the responsibility of FZK Karlsruhe a 140-GHz, 1 MW gyrotron for the stellarator Wendelstein 7-X operated with pulses up to 30 min has been developed in a collaboration between European research laboratories and Thales Electron Devices (TED) in France as industrial partner. Two prototype tubes have been manufactured and tested before the series production started. The first series tube has already been delivered and successfully tested. The obtained results are presented below. In total seven such tubes will be fabricated.

For use at ITER the development of a 170 GHz coaxial cavity gyrotron with an RF output power of 2 MW, CW is underway within a European cooperation. The design of the components of the first industrial prototype has already been finished and the fabrication of the tube is in progress.

Delivery is expected for spring 2006. The development work is mainly based on previous experimental investigations performed at FZK on a short pulse (~ms) 165 GHz coaxial cavity gyrotron [9]. To verify the design of components of the industrial prototype, a short pulse pre-prototype of the coaxial gyrotron has been operated at 170 GHz using the same cavity and RF output system and a very similar electron gun. In addition, a low power test facility for measuring the performance of the RF output system has been developed. Status of the gyrotron development and results with the pre-prototype are reported below.

Frequency tunable gyrotrons are of interest for controlling instabilities in magnetically confined fusion plasmas. In previous short pulse experiments the possibility of tuning the frequency of the gyrotron by variation of the magnetic field has been demonstrated [10]. For use at ASDEX-Upgrade at the Max-Planck-Institute of Plasma Physics in Garching, Germany, a step tunable gyrotron operating at frequencies between 105-140 GHz is under development in cooperation with the institute of applied physics, Nizhny Novgorod, Russia [11].

II. 140 GHz, 1 MW, CW, CONVENTIONAL GYROTRON

A. Design

The main design parameter of the 140 GHz gyrotron for the stellarator Wendelstein 7-X (W7-X) are summarized in Table I. The gyrotron uses a diode type magnetron injection gun with an emitter radius of 50 mm. The emitting current density is 2.5 A/cm² at the beam current I₀=40 A. The design value of the velocity ratio is α = 1.3. A schematic view of the gyrotron is shown in Fig. 1.
TABLE I
DESIGN PARAMETERS OF THE 140 GHZ GYROTRON

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>RF output power</td>
<td>1 MW</td>
</tr>
<tr>
<td>Accelerating voltage</td>
<td>81 kV</td>
</tr>
<tr>
<td>Beam current</td>
<td>40 A</td>
</tr>
<tr>
<td>Frequency</td>
<td>140 GHz</td>
</tr>
<tr>
<td>Operating cavity mode</td>
<td>TE_{28,8}</td>
</tr>
<tr>
<td>Mode purity of cavity</td>
<td>99.9%</td>
</tr>
<tr>
<td>Electron beam radius at cavity</td>
<td>10.1 mm</td>
</tr>
<tr>
<td>Cavity radius</td>
<td>20.48 mm</td>
</tr>
<tr>
<td>Cavity length</td>
<td>14.5 mm</td>
</tr>
<tr>
<td>Launcher taper</td>
<td>0.004 rad</td>
</tr>
<tr>
<td>Launcher efficiency</td>
<td>98%</td>
</tr>
<tr>
<td>RF beam radius at window</td>
<td>23.3 mm</td>
</tr>
<tr>
<td>Window aperture</td>
<td>88 mm</td>
</tr>
</tbody>
</table>

The beam tunnel between the gun and the cavity consists of an aperiodic loaded structure composed by a stack of copper and dielectric rings in order to suppress spurious oscillations. The RF cavity has been designed to operate in the TE_{28,8} mode. It is a conventional cylindrical cavity with a length of 14.5 mm and a diameter of 40.96 mm, a linear input taper of 2.5° and a non-linear output uptaper with an input angle of 3°. Mode conversion has been strongly reduced by use of smooth transitions between cylindrical and taper sections with a transition length of 4 mm at the input and of 6 mm at the output taper.

Fig. 1. Schematic view of the gyrotron.

Special care has been devoted to the design of the quasi-optical mode converter in order to keep the amount of stray radiation as low as possible. The operating mode belongs to a class of cavity modes for which the ratio of caustic to cavity radius is approximately 0.5. For this case, the perturbations of a dimpled-wall cavity with a length of 1.8 mm and a diameter of 40.96 mm, a linear input taper of 2.5° and a non-linear output uptaper with an input angle of 3°. Mode conversion has been strongly reduced by use of smooth transitions between cylindrical and taper sections with a transition length of 4 mm at the input and of 6 mm at the output taper.

The output vacuum window unit uses a single, edge-cooled CVD-diamond disk [13] with an outer diameter of 106 mm, a thickness of 1.8 mm (four half wavelengths inside the material) and a window aperture of 88 mm. The average loss tangent of the disk had been determined in a low-power measurement to 4.10^{-5}. For this loss tangent, the losses in the disk are calculated to be about 700 W for an output power of 1 MW. The diamond disk is brazed to copper cuffs with a Cu/Ag-based brazing at about 750-850°C. This avoids corrosion of the braze by water cooling and allows higher baking temperatures of the gyrotron.

To increase the overall efficiency the gyrotron can be operated with a depressed collector. The collector with the mirror box, the last mirror of the quasi-optical mode converter system and the window unit are on ground potential, whereas the beam tunnel the cavity, launcher and the first two mirrors are at a depression voltage \( V_{body} \). At the design values the cathode voltage is set to \( V_{cath} = -54 \) kV and the body to \( V_{body} = +27 \) kV.

**B. Experimental Results**

**Prototype tubes:**

During the development phase two gyrotrons, a pre-prototype tube called "Maquette" and an improved version, the prototype tube, have been fabricated and tested. With these tubes, in particular with the prototype tube, the specified performance has almost been demonstrated. However, two problems remained, namely (1) the output power of 1 MW was not completely achieved, and (2) the pulse length of 30 minutes could not be obtained even with reduced output power due to pressure rise.

The first problem was assumed to be due to a degraded electron beam quality caused by an inhomogeneous emission from the cathode surface. This inhomogeneity may deteriorate the quality of the electron beam [14]. Other effects as for example spurious mode oscillations or a misalignment of the gyrotron might be excluded as this effect has not been observed in the pre-prototype tube. The suspicion of non uniform electron emission is strengthened by a visual inspection of the cathode after dismantling the tube. The pictures taken with a scanning electron microscope clearly showed different surface structures with a different surface roughness or porosity.

The problem of pressure rise at long pulses was found to be related with heating up of internal components due to the stray losses. Though the stray radiation turned out to be only 3% (the internally absorbed one is only about 1% of the output power), the pulse length of the gyrotron was limited to 939 s at an output power of 539 kW due to a pressure increase inside the gyrotron. In particular, the temperature of...
the ion getter pumps placed inside the mirror box was measured to rise up to values of more than 260°C during the pulse.

Knowing the reasons for the limitation in output power and in pulse length, the development phase for the gyrotron has been finished and seven series gyrotrons and eight superconducting magnets have been ordered.

**First series tube:**

According to the experience with the prototype tube a quality assurance of the emitter ring has been performed by inspecting the surface of the emitter with a scanning electron microscope before using the emitter in the tube.

The problem with overheating of the internal ion getter pumps due to stray radiation has been solved by placing the pumps outside the gyrotron and improving the shielding against RF-radiation. Fig. 2 shows a photography of the first series tube installed in the test facility at FZK.

**Fig. 2. Photography of the 1st series tube at the test facility**

The first series tube arrived at FZK in February 2005 and was tested in short and long-pulse operation. Fig. 3 shows the dependence of output power on the electron beam current. Opposite to the results of the prototype, the output power does not show a saturation up to beam currents of 50 A proving the good quality of the electron emitter ring. The corresponding output power was 1.15 MW with an efficiency of 30%. For this measurement the magnetic field and the electron beam radius at the cavity was kept constant at 5.53 T and 10.36 mm, respectively. It turned out that the output power is strongly dependent on the beam radius. This is the reason why at 26.5 A practically no output power has been observed (Fig. 3). For the low beam current, the beam radius had to be changed in order to excite the desired $TE_{28,8}$ mode at a reasonable output power.

**Fig. 3. Dependence of output power on the electron beam current.**

Field profile measurements were performed by inserting a target into the RF-beam. Fig. 4 shows the RF beam pattern in different distances from the window. The beam reconstruction yielded a Gaussian beam content of 97.5%. However, a shift of 12 mm has been found for the RF beam in a direction opposite to what had been found during measurements with the prototype. It is thought that this is due to the tolerances of the mirror system especially in position and angle of the first quasi-elliptical one, which are very sensitive to the position of the beam at the window.

**Fig.4. Profile measurements of the RF beam in different distances from the window.**

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). Fig. 5 shows as an example the frequency shift during a 1s pulse with 570 kW output power.

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 10.45 mm. At lower beam radii, arcing occurs, at higher radii a wrong mode (or the counter-rotating mode) is excited. The optimum value of the beam radius decreases slightly with decreasing cavity field and beam current.
It is interesting to know the individual power distribution that is to know the internal, external stray radiation, the Ohmic losses, the generated power and so on. The water cooling loops at the test facility at FZK Karlsruhe are equipped with a number of thermocouples which allow very accurate individual calorimetric measurements of different components as for example parts of the beam tube, polarizers, preload and an absorber placed inside the chamber. The tube itself is also equipped with thermocouples in order to measure the power dissipated in the different components. Based on the individual calorimetric measurements a power balance of the series tube has been performed as is summarized Table II. Compared to the prototype the values are similar, however, the losses of the diamond window are increased by a factor of 2.

**TABLE II**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Power (kW)</th>
<th>Relative power / %</th>
<th>Power (kW)</th>
<th>Relative power / %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Generated power</td>
<td>970±50</td>
<td>100</td>
<td>607±30</td>
<td>100</td>
</tr>
<tr>
<td>Ohmic losses</td>
<td>40±8</td>
<td>4.2</td>
<td>26±5</td>
<td>4.2</td>
</tr>
<tr>
<td>Internal stray radiation</td>
<td>9.6±2</td>
<td>1.0</td>
<td>7.5±1.5</td>
<td>1.2</td>
</tr>
<tr>
<td>Window losses</td>
<td>1.5</td>
<td>0.2</td>
<td>1.0</td>
<td>0.2</td>
</tr>
<tr>
<td>Output power</td>
<td>920±45</td>
<td>95</td>
<td>569±30</td>
<td>93.8</td>
</tr>
<tr>
<td>External stray radiation</td>
<td>14±3</td>
<td>1.4</td>
<td>12±3</td>
<td>1.9</td>
</tr>
<tr>
<td>Directed power</td>
<td>906±45</td>
<td>93.5</td>
<td>557±28</td>
<td>91.8</td>
</tr>
</tbody>
</table>

The theoretically predicted value of 2% for the stray radiation agrees well with the measured total value of about 3% resulting from 1.2% of internal and 1.9% of external stray losses. It is thought that due to mechanical tolerances a further reduction becomes difficult.

The highest output power obtained for three minutes pulses (limitation of the HV power supply at the Forschungszentrum Karlsruhe) was 920 kW with a directed power of 905 kW. The directed power is the power measured inside the load, the preload, on the mirrors and polarizers. The efficiency of the gyrotron for this pulse was 27.9% without depressed collector and 43.4 % with a depression voltage of 28.5 kV. The (averaged) electron beam current was 40.6 A, the accelerating voltages 81 kV. Fig. 6 shows the time dependence of the gyrotron parameters during this pulse.

A reduction in beam current to values less than 30 A allows operation of the gyrotron with pulse up to CW. Fig. 7 shows the beam parameters for a pulse length slightly above 30 minutes (1893s). The pressure increase during this pulse is less than a factor of 2 and stays well inside the 10⁻⁹ mbar range. In these plots also a diode signal for the output power is shown. The diode is installed in front of the first mirror and detects a small part of the output beam. This signal is very stable during the pulse. Nevertheless, it is not completely clear whether it is always proportional to the output power.

The reliability of the gyrotron at high output power has been checked in long pulse operation. Eight consecutive pulses were successful at a power level of about 900 kW and a pulse length of 180 s. The ninth pulse ended due to arcing inside the tube after 168 s. After this, short pulse operation was necessary with a few pulses in order to recover the behaviour of the gyrotron.

It is pointed out that though the output power of 1000 kW has not been achieved – the directed power (Gaussian content) is 906 kW in agreement with the specifications. It is thought that by increasing the electron beam current by ~10% (from 41 A to 45 A) also the output power and the directed RF power should be increased by a similar amount. Due to lack of time this has not been proven. Though not all measurements which were foreseen during these tests have been performed, the tests were finished and the gyrotron was delivered to IPP Greifswald where operation at full performance with pulses up to 30 minutes can be done.
III. 170 GHz, 2 MW, CW, COAXIAL GYROTRON

Investigations performed at FZK Karlsruhe during the last years have demonstrated the feasibility of manufacturing a 2 MW, CW coaxial cavity gyrotron at 170 GHz and information necessary for a technical design has been obtained [9,15]. Based on these results the development work on a first industrial prototype of a 2 MW, CW, 170 GHz coaxial cavity gyrotron for ITER has started in cooperation between European research centers (FZK Karlsruhe, CRPP Lausanne, HUT Helsinki) and a European industrial partner (Thales ED, Velizy, France) [16].

In parallel to the work on the industrial prototype tube, the experimental 165 GHz coaxial cavity gyrotron used previously at FZK, has been modified for operation at 170 GHz. This short pulse (≤ 10 ms) experimental gyrotron ("pre-prototype") operates in the same TE_{34,19} mode and uses the same geometry of cavity with uptaper, launcher and mirrors as foreseen for the industrial prototype and, in addition, a very similar electron gun. Experimental investigations on the pre-prototype have been performed recently in order to verify the design of the main components of the industrial tube under relevant conditions.

In table III the main design parameters both for the 2 MW, CW prototype gyrotron and for the short pulse pre-prototype tube are summarized. The SC-magnet available at FZK for experiments with the pre-prototype delivers only a magnetic field up to about 6.7 T. Due to this the accelerating voltage had to be reduced to values below 80 kV, in order to be able to excite the TE_{34,19} mode at 170 GHz. According to simulations, operation at a lower voltage results in an RF output power reduced to about 1.5 MW, depending on the finally obtained magnetic field.

| TABLE III |
| DESIGN PARAMETERS OF PROTOTYPE AND PRE-PROTOTYPE OF THE 170 GHZ COAXIAL GYROTRON |
| prototype | pre-prototype |
| operating cavity mode | TE_{34,19} |
| frequency, f / GHz | 170 |
| RF output power, P_{out} / MW | 2 | ~1.5 |
| beam current, I_{b} / A | 75 |
| accelerating voltage, U_{acc} / kV | 90 | ≤ 80 |
| cavity magnetic field, B_{cav} / T | 6.87 | ~6.7 |
| velocity ratio, α | ~1.3 |

A. The 170 GHz pre-prototype coaxial gyrotron

A schematic layout of the pre-prototype tube is shown in Fig. 8. The coaxial magnetron injection gun (CMIG) is similar as used in the previous 165 GHz gyrotron [17]. At I_{b} = 75 A the emitting current density is about 4.2 A/cm². The inner part of the coaxial insert is water cooled and its position can be adjusted under operating conditions. Special care has been taken in designing the geometry of the bottom part of the cathode body and of the insert in order to avoid regions in which electrons can be trapped and which may cause a Penning discharge [15].

In order to keep the Ohmic losses at the cavity wall below 1 kW/cm² (ideal copper at 293 K) for 2 MW RF output power, the TE_{34,19} mode has been selected as the operating mode [18], instead of the TE_{31,17} mode, which was used in the previous experiments at 165 GHz. The corresponding peak losses at the insert are expected to be less than 0.1 kW/cm². The geometry of the cavity is shown in Fig. 9. Inside the cavity the coaxial insert is longitudinally corrugated and down-tapered with an angle of 1°. The problem of mode competition has been investigated with a time dependent, self-consistent multimode code, considering up to 13 competing modes.

![View of the 170 GHz pre-prototype gyrotron](image1)

![Geometry of the 170 GHz, TE_{34,19} coaxial cavity.](image2)
one quasi-elliptical mirror followed by a toroidal mirror and a phase correcting mirror with an adapted, non-quadratic surface contour (Fig. 10). Because of limitations in the accuracy of mechanical fabrication of the surface structure of the non-quadratic mirror, a compromise had to be made between the Gaussian content of the RF output beam and the amount of microwave stray radiation [19]. According to calculations the total amount of stray losses is expected not to exceed a value of 5 % to 6 % of the output power $P_{\text{out}}$.

The window is a single quartz disk (aperture = 100 mm) with an optical thickness of $15 \lambda / 2$ at 170 GHz, whereas for the 2 MW prototype a $5 \lambda / 2$ disc made of CVD diamond is foreseen.

The collector and the gyrotron body are insulated from ground in order to allow operation with a depressed collector.

**Electron gun and electron beam:**

The performance of the electron gun has been found to be in good agreement with the design objective as far as the properties have been observable during the gyrotron operation. No limitations on high voltage performance due to build up of a Penning discharge have been observed by extending the pulse length up to 100 ns / 40 ms at $I_b = 1 A / 17 A$. Stable operation up to $I_b = 80 A$ and $U_{\text{acc}} = 80 kV$ has been observed without any beam instabilities. The current to the insert was measured to be below 0.1% of the beam current, in agreement with the results of previous experiments.

**B. Operation of the pre-prototype and recent results:**

When starting the gyrotron operation strong parasitic low frequency (LF) oscillations at frequencies of around 259, 328 and 68 MHz have been observed at beam currents $I_b \geq 10 A$ and accelerating voltages $U_{\text{acc}} \geq 40 kV$. The amplitude of these LF oscillations could become very large, completely preventing a stable gyrotron operation. The most severe LF oscillation appeared at $\sim 259$ MHz. The appearance of those LF oscillations was unexpected, in particular, because no such oscillations have been observed in the previous 165 GHz coaxial gyrotron with very similar geometrical dimensions (in comparison to the wavelength of the LF frequencies). Finally the oscillations were completely suppressed by placing absorbing material ("eccosorb") around the bottom end of the insert. With the damping material no LF oscillations have been observed for beam currents up to about 80 A. Modeling of the LF oscillations with the commercial "CST Microwave Studio" code have been performed. The results are in good agreement with the experimental observations. As input for the code the geometry of the gyrotron including the warm bore of the superconducting (SC) magnet has been modeled in great detail. The simulations have shown that the coaxial part formed by the gyrotron body and the bore hole of the SC magnet has a strong influence on the LF oscillation, in particular, on the oscillation at 259 MHz.

**Cavity and RF-interaction:**

The microwave experiments were carried out in short-pulse operation, up to about 10 ms, limited by the power loading at the collector surface. First the inner conductor has been radially aligned with respect to the electron beam within ±0.1 mm and the concentricity between the electron beam and the cavity wall has been verified. In general the results can be summarized as follows: The nominal co-rotating $\text{TE}_{34,19}$ mode at 170 GHz has been excited stably in single-mode operation over a wide parameter range. Fig. 11 shows a typical behavior of the RF output power measured as a function of the applied accelerating voltage $U_{\text{acc}}$. The corresponding variation of the beam current $I_b$ with $U_{\text{acc}}$ due to the Schottky effect is indicated too. The magnetic field has been kept constant at $B_{\text{cav}} = 6.718$ T. The beam radius has been optimized for maximum output power by varying the magnetic compression ratio. With increasing beam voltage first the $\text{TE}_{34,19}$ mode at 170.02 GHz occurs followed by the $\text{TE}_{35,19}$ mode at 167.85 GHz above $U_{\text{acc}} \sim 73$ kV. At voltages above $\sim 80$ kV the $\text{TE}_{32,19}$ mode at 165.74 GHz has been observed. The experimentally observed mode sequence with increasing beam voltage is not in agreement with the theoretical results. According to numerical simulations the $\text{TE}_{33,19}$ mode should not occur at all under this conditions. In comparison with simulations the additional appearance of the $\text{TE}_{33,19}$ mode as competitor results in a reduction of the oscillating range of the nominal $\text{TE}_{34,19}$ mode on the high voltage side. Thus the excitation of the $\text{TE}_{34,19}$ mode ends at the fairly low voltage $U_c \sim 73$ kV with a velocity ratio $\alpha = 1.1$ and a maximum RF output power of $P_{\text{out}} = 1.15$ MW with a corresponding...
efficiency of about 20% (without depressed collector). The reasons for the discrepancy between theory and experiment are not yet clear and need further investigations. In particular, the influence of alignment on the gyrotron performance will be studied in more detail.

Quasi-optical (q.o.) RF-output system:

The performance of the q.o. RF output system has been studied both at low power levels ("cold") and at high power ("hot") with the pre-prototype gyrotron. A good agreement has been found between the "cold" and "hot" measurements and calculations. However, an error in performing the optimization of the mirrors has been discovered. A mistake has been made in calculation the launcher field which has been used for optimization of the mirrors. The mirrors have been redesigned and manufactured in the meantime. "Cold" measurements performed with the redesigned mirrors are in good agreement with design calculations as shown in Fig. 12. "Hot" measurements on the pre-prototype will be performed next. The design of the q.o. RF output system has been frozen for use in the industrial prototype tube.

Further improvements of the q.o. RF output system, in particular, to increase the Gaussian content in the output beam are desired and have high priority.

Microwave stray losses inside the tube:

The mirror box has a total of three relief windows in addition to the main RF output window. All the windows with discs out of fused silica have a diameter of 100 mm. The amount of stray losses inside the tube has been determined by measuring the power radiated through one relief window with a sensitive bolometer both for the case when the two other relief windows were covered either with a reflecting metal plate or with a good absorber. As a result stray losses of about 8% have been estimated for operation in the nominal TE_{34,19} mode at 170 GHz. In the TE_{33,19} mode at 167.85 GHz the stray losses are approximately three times as high, namely about 22%. This is mainly due to the increased reflection from the RF output window of about 9%. The absolute value of power radiated through one relief window has been measured to be 0.0074\times P_{out} at 170 GHz and 0.019\times P_{out} in the TE_{33,19} mode. The power radiated through the relief windows was approximately the same in all windows, confirming the assumption of a nearly uniform distribution of the stray losses inside the mirror box.

Operation with internal microwave absorbers:

In order to reduce the amplitude of the captured stray radiation inside the prototype tube, internal microwave absorbers are foreseen. To determine the absorption efficiency of such an internal load, a test absorber consisting of an array of four water cooled Al_{2}O_{3} tubes (diameter = 20 mm, length = 100 mm) has been installed inside the mirror box as shown in Fig. 13. According to calorimetric measurements 2.2% of P_{out} corresponding to about 25% of the microwave stray losses are absorbed in the tubes. This amount is as large as 3 times the power radiated through one relief window with 100 mm diameter. The operation with the internal absorbing tubes did not show any significant influence on the microwave generation.

C. Status of the industrial prototype

All components for the industrial prototype have already been designed and are under fabrication. Internal absorber consisting of similar Al_{2}O_{3} tubes as investigated in the pre-prototype are expected to dissipate more than 50% of the stray losses captured inside the gyrotron. The RF output window will use a 1.852 mm CVD disk (5/2\lambda) with an aperture of 96 mm. The first prototype tube is expected to be delivered in spring 2006. A suitable SC-magnet has already been ordered and is under fabrication. A facility for testing the 2 MW, CW gyrotron is under construction at CRPP Lausanne, Switzerland. Tests with the first prototype tube are foreseen to start in summer 2006.

IV. FREQUENCY STEP TUNABLE GYROTRON

A. Design

In former experiments operation of a gyrotron with an almost constant microwave output power over a wide frequency range (104-166 GHz) by varying the value of the magnetic field of the SC-magnet has been demonstrated. A fast (~ in second range) frequency tuning over a range of ~15 GHz in steps of 3 GHz has been performed using a hybrid magnetic system (superconducting magnet in combination with a normal conducting magnet) [21].

In a collaboration between FZK Karlsruhe, IPP Garching and the Institute of Applied Physics (IAP), Nizhny Novgorod, Russia, a 1 MW, frequency tunable long pulse gyrotron (10s) for suppression of NTMs at the tokamak ASDEX-Upgrade is under development. For this gyrotron 9 modes from TE_{17,6} (105 GHz) to TE_{23,8} (143 GHz) have been chosen with the TE_{22,8} mode at 140 GHz. In parallel to the work on the long-pulse gyrotron at Nizhny Novgorod a
short pulse prototype has been designed at FZK mainly to study the q.o. RF output system [22]. For broadband operation, the q.o. mode converter has to be optimized for all 9 modes. The optimized q.o. mode converter consists of a dimpled-wall antenna and three mirrors - first a large quasi-elliptical mirror followed by two phase correcting mirrors with a non-quadratic shape of the surface contour. Next the performance of the q.o. mode converter will be studied first at low power before measurements in the short pulse tube will be made.

Furthermore, the operation over a wide frequency range requires a window with a broad band transmission characteristic, that is either a adjustable double-disk window or a Brewster window. Though the first frequency tunable long-pulse gyrotron is planned to be equipped with a tunable double-disk window, a Brewster window with a CVD diamond disc would be preferable. For such a Brewster window a diamond disc with a thickness of 1.7 mm and a diameter of 140 mm is available at FZK Karlsruhe. The loss tangent of the disc has been measured to be in the 10⁻⁵ range. Using this CVD disk, a draft design of a Brewster window with an aperture of 50.2 mm and a length of 150 mm has been done. The brazing of copper cuffs on the tilted CVD disk is under investigation.

V. SUMMARY

The development of 1-MW, CW gyrotrons for the stellarator W7-X has been successfully finished. A first gyrotron out of a series of 7 tubes has been successfully tested at FZK up to 3 min at full performance. The tube has been installed at site of W7-X in Greifswald, where tests up to 30 min at full performance will be done.

A 2 MW, CW, 170 GHz coaxial cavity gyrotron is under development within a European cooperation. A first industrial prototype has been designed and is under fabrication. The main components of the prototype tube have been verified with an experimental pre-prototype tube at FZK.

A 1 MW, 10s, stepwise frequency tunable gyrotron is under development. At FZK the q.o. mode converter is under investigation. In addition, a Brewster window with a 140 mm CVD diamond disk is under development.

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