# Recent Results of the 2 MW-0.17 THz European Pre-Prototype Coaxial-Cavity Gyrotron for ITER

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## Abstract

A 2 MW, CW, 0.17 THz coaxial-cavity gyrotron for electron cyclotron heating and current drive in the International Thermonuclear Experimental Reactor (ITER) is under development within the European Gyrotron Consortium (EGYC*), a cooperation of several European research institutions. To support the development of the industrial prototype of a CW gyrotron, a short-pulse tube (pre-prototype) is operated at KIT Karlsruhe (former FZK, Karlsruhe) for experimental verification of the design of critical components, like the electron gun, beam tunnel, cavity and quasi-optical (q.o.) mm-wave output coupler. Recently a significant progress has been achieved. In particular, output power of up to 2.2 MW at 30 % output efficiency (non-depressed collector operation) has been obtained in single-mode operation at 0.17 THz with a fundamental Gaussian mode content of almost 96 %. After replacement of the narrow-band fused-silica output window by a broadband silicon-nitride Brewster window (frequency tunable gyrotron) first experiments gave an output power of 1.8 MW with an efficiency of 26% in the $TE_{28,16}$ mode at 0.1413 THz. In addition, in the next azimuthal neighbor mode $TE_{29,16}$ at 0.1433 THz, an output power of 1.25 MW has been generated with an efficiency of 23%. Measurements of the intensity profiles of the mm-wave output beams show very good mode purity also for these other frequencies and modes.

## 1. Introduction

Gyrotrons are foreseen as microwave sources for electron cyclotron heating (ECH), current drive (CD) and stabilization of plasmas in the International Thermonuclear Experimental Reactor (ITER). First plasma experiments in ITER are planned to begin in 2018 [1]. At that time, the ITER ECH & CD system is expected to have an installed mm-wave power of 26 MW at 0.17 THz, practically in continuous wave (CW) operation in order to deliver up to 22 MW power into the plasma. The delivery of the gyrotrons is equally shared between Japan [2], Russia [3] and Europe (EU) [4]. To fulfill the needs of ITER "conventional" 1 MW gyrotrons with a hollow waveguide cavity are under development in Japan and Russia.

However, in order to keep the number of the required gyrotrons and magnets as low as possible, to reduce the costs of the ITER 26 MW, 0.17 THz ECH & CD system and to allow four compact upper launching antennas for plasma stabilization, higher mm-wave power per tube (2MW) is desirable. Demands for upgrading the ECH power for the future operation of ITER up

* EGYC is a collaboration among CRPP, Switzerland; KIT, Germany; HELLAS, Greece; CNR, Italy; ENEA, Italy

to ~40 MW are already now under discussion. Cylindrical waveguide gyrotron cavities are not suitable for this high frequency, high power regime because of high Ohmic wall losses and/or mode competition problems. However, in coaxial cavities the existence of the longitudinally corrugated inner conductor reduces the problems of mode competition and limiting current, thus allowing one to use even higher-order modes with lower Ohmic attenuation than in cylindrical cavities [5]. In addition, the inner rod enables a specific voltage depression scheme for energy recovery and ultra-fast frequency step tuning just by applying an appropriate voltage to this coaxial insert. CVD-diamond windows with a transmission capability of 2 MW, CW are feasible [6,7].

A European 2 MW, CW, 0.17 THz coaxial-cavity gyrotron for use in ITER is being developed within the EU gyrotron consortium EGYC [4,5]. The parameters of this gyrotron are described in Chapter 2. In Chapter 3 record results of mm-wave generation achieved with an upgraded tube will be reported. Chapter 4 summarizes the results and draws several conclusions.

## 2. Parameters of the 0.17 THz Coaxial-Cavity Gyrotron

The design specifications for the European (EU) 0.17 THz, 2 MW, CW coaxial-cavity gyrotron for the 26 MW (installed) ECH&CD system on ITER are summarized in Table 1. The coaxial arrangement reduces mode competition in the gyrotron interaction cavity. Thus with cavity modes of very high order (eigenvalue $\chi$ >100) stable single-mode operation can be obtained in the multi-megawatt output power range.

| | |
|---|---|
| Operating cavity mode | $TE_{34,19}$ |
| Frequency, $f$ | 0.17 THz |
| mm-wave output power, $P_{out}$ | 2 MW |
| Beam current, $I_b$ | 75 A |
| Accelerating voltage, $U_c$ | 90 kV |
| Velocity ratio, $\alpha$ | ~ 1.3 |
| Cavity magnetic field, $B_{cav}$ | 6.87 T |
| Efficiency with SDC | > 50 % |

Table 1. Design specifications for the European coaxial-cavity CW gyrotron for ITER.

However, a consequence of the use of high-order volume cavity modes is among other things, the significant increase of the complexity of the antenna launcher of the internal quasi-optical (q.o.) mm-wave output coupler which is needed for conversion of the very high-order coaxial-cavity mode into the fundamental free space Gaussian mode.

A first industrial prototype of a CW coaxial-cavity gyrotron, which was manufactured at Thales Electron Devices (TED) in France, has already been tested at CRPP Lausanne [4]. Mainly problems with high voltage stand-off inside the tube did not allow to operate the gyrotron at nominal parameters. As a consequence of this an output power of only 1.4 MW (instead of 2 MW) has been achieved. The reason for the limitations was not clear and is under investigation. To support the activities on the industrial prototype, experimental studies on a short pulse (≤ few ms) experimental 0.17 THz coaxial-cavity gyrotron ("pre-prototype") are performed at KIT (Fig. 1). The pre-prototype tube is the basis for the industrial prototype and utilizes the same $TE_{34,19}$-cavity mode and the same coaxial cavity with up-taper, launcher and

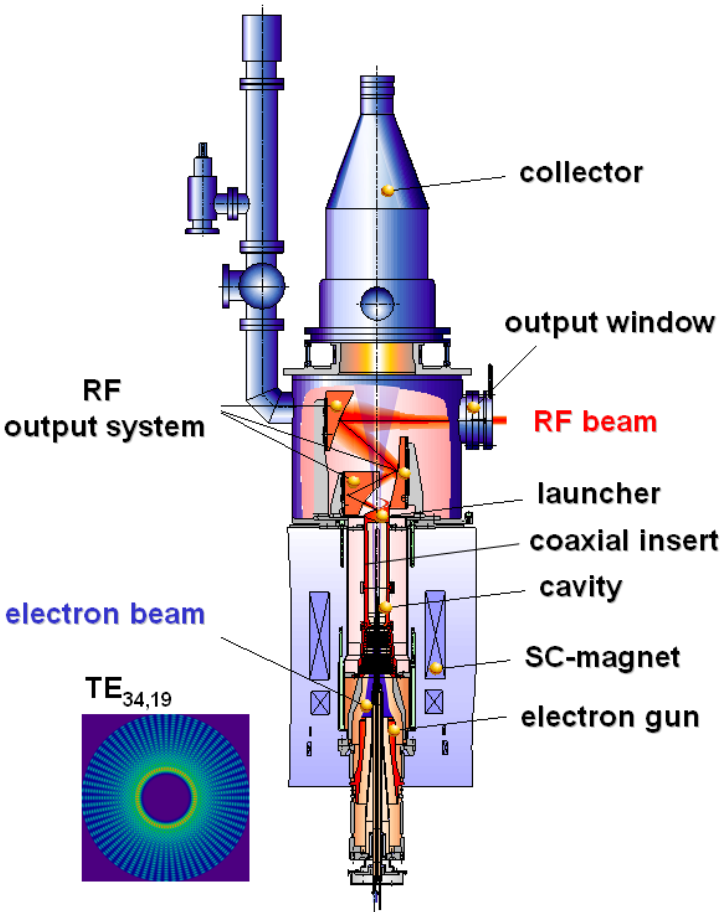


Fig. 1. Short-pulse 0.17 THz, 2 MW coaxial-cavity gyrotron at KIT (pre-prototype tube).

mirrors as designed for the industrial prototype and in addition, it uses a very similar temperature limited coaxial magnetron injection electron gun (CMIG) and a similar beam tunnel. Therefore the performance of the gyrotron and its main components - electron gun, beam tunnel, coaxial cavity and q.o. mm-wave output coupler – can be studied under fairly relevant conditions and unexpected problems can be discovered and investigated in advance.

Due to the technical limitation of the superconducting (SC) magnet in use at KIT, the gyrotron was first operated at a reduced magnetic field of approximately 6.7 T and, in order to be able to excite the $TE_{34,19}$ mode at 0.17 THz, also at a beam voltage below 80 kV. Owing to this a reduced value of the generated mm-wave output power around 1.5 MW was measured. To be able to operate the short-pulse pre-prototype under the same conditions as the industrial tube, the modifications described in the following chapter have been applied. After these changes the main nominal parameters, shown in Table 1, are the same for the TED 2 MW, CW industrial prototype and for the KIT pre-prototype tube.

## 3. Millimeter-Wave Power Generation

Recently the following modifications have been performed on the pre-prototype gyrotron:

(i) Since the SC gyrotron magnet in use at KIT limits the maximum value of the cavity magnetic field to around 6.7 T, an additional normal conducting (NC) coil has been wound directly on the gyrotron body around the location of the cavity in order to increase the cavity magnetic field to the nominal value of 6.87 T.

(ii) The shape of the anode of the CMIG has been redesigned to generate a velocity ratio $\alpha = 1.3$ at the nominal operating parameters (90 kV, 75 A, 6.87 T).

(iii)To suppress parasitic high-frequency oscillations a novel beam tunnel (Fig. 2) has been designed, fabricated and installed in the tube. The main modification consists in introducing irregular corrugations (longitudinal slots) in the copper rings, in order to destroy the azimuthal symmetry and thus to suppress circular symmetric electric modes which were only weakly attenuated in the former azimuthally symmetric beam tunnel structure [8,9]. Further on, the arrangement of the ring structure is conical in difference to a stepwise cylindrical arrangement of the previous beam tunnel.

(iv)A new q.o. output coupler has been installed in the gyroton. The design of the significantly improved system is based on a launcher optimized with a novel optimization method [10]. The launcher can be seen as an in-waveguide line of mode-converting and phase-correcting mirrors with non-quadratic surface contour function. Before installation in the gyrotron the new q.o. mode converter has been verified in “cold” measurements employing a low-power $TE_{34,19}$-mode generator and an in-house built vector network analyzer [11].

Experiments performed with the modified gyrotron showed a very stable operation of the tube up to $U_c$= 93kV and $I_b$ = 80 A. In agreement with expectations, the increase of the magnetic field by applying the NC-coil resulted in a shift of the excitation region of the $TE_{34,19}$ mode to higher values of cathode voltage. Around the nominal magnetic field value (6.87 T) a maximum mm-wave output power $P_{out} \approx 2.2$ MW has been obtained at $U_c$= 93kV and $I_b$=80 A with an efficiency of around 30 % with 1 ms pulse duration in non-depressed collector operation. If a CVD-diamond window would be installed instead of the fused-silica window, the output power would be 2.3 MW at an efficiency of 31% due to lower mm-wave absorption in diamond.

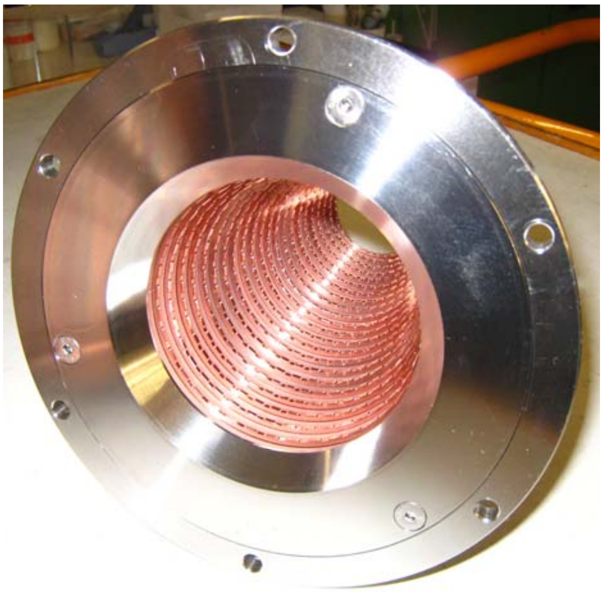

Fig. 2. Photo of the new beam tunnel with irregularly longitudinally corrugated copper rings.

The measured mm-wave output power and efficiency versus the cathode voltage is shown in Fig. 3. The figure also contains the results of numerical simulations performed with the KIT multi-mode, self consistent code SELFT taking into account 5 % transverse electron velocity spread. The agreement between experiment and simulations is very good if approximately 10 %

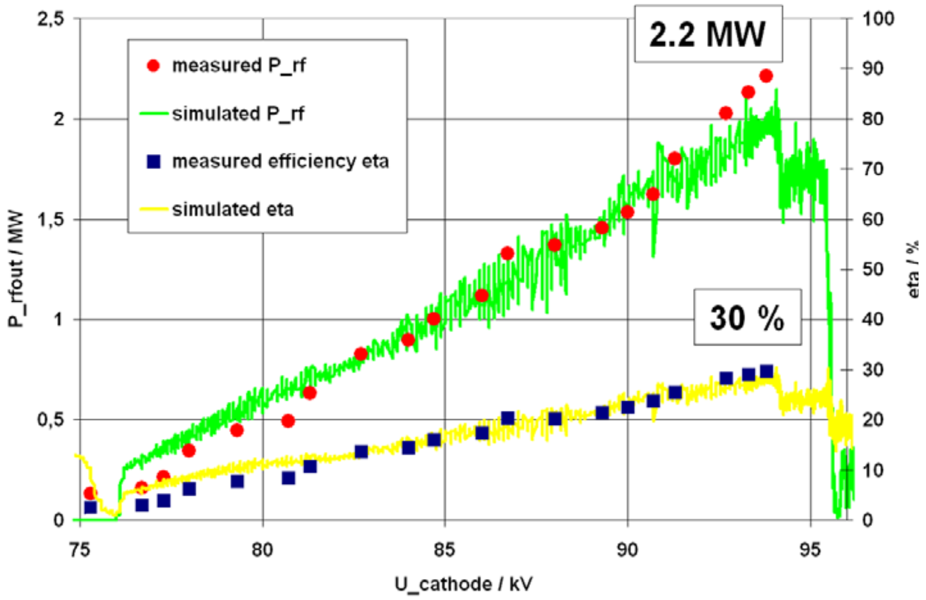


Fig. 3. Measured and calculated gyrotron output power and efficiency vs. cathode voltage at the nominal magnetic field of 6.87 T.

of the generated output power in the nominal mode is assumed to be lost inside the tube due to stray radiation, Ohmic losses and absorption in the output window (see Table 2). The operation of the gyrotron with the modified beam tunnel resulted in a significant improvement of the stability and single-mode generation over a very broad parameter range. No parasitic high-frequency oscillations excited outside the gyrotron cavity could be found at the nominal parameters of the gyrotron. Due to the use of the new q.o. mm-wave output system, the amount of stray radiation inside the tube has been slightly reduced to $P_{stray}$ ~(7±2)% of the output power $P_{out}$, to be compared with (8±2)% with the previous launcher. The numerical multi-mode simulations suggest that approximately half of $P_{stray}$ could result from modes at different frequencies, which are excited simultaneously with the $TE_{34,19}$ mode in the cavity. The theoretical balance of the internal losses and the stray radiation captured inside the tube is shown in Table 2. To verify these theoretical estimations more detailed investigations are planned. Fig. 4 shows the intensity distribution of the output beam at two different distances from the window. From the phase reconstruction of the measured "hot" beam profiles a Gaussian mode purity of almost 96% has been deduced.

| | Losses @ nominal mode | Total stray radiation |
|---|---|---|
| Spurious cavity modes ($TE_{n,19}$ ; n=36,35,33,32) | --- | 3 % |
| Ohmic losses of cavity and uptaper | 2.2 % | --- |
| Mode conversion losses of uptaper | 0.2 % | 0.2 % |
| Ohmic losses of launcher | 1.8 % | --- |
| Reflection of launcher | 0.3 % | 0.3 % |
| Stray radiation of launcher | 0.7 % | 0.7 % |
| Ohmic losses of 3 mirrors | 0.5 % | --- |
| Diffraction losses of 3 mirrors | 1.1 % | 1.1 % |
| Absorption losses of quartz window | 3.3 % | --- |
| Reflection of window | 0.4 % | 0.4 % |
| **Total** | **10.5 %** | **5.7 %** |

Table 2. Estimated relative internal mm-wave losses and internal stray radiation.

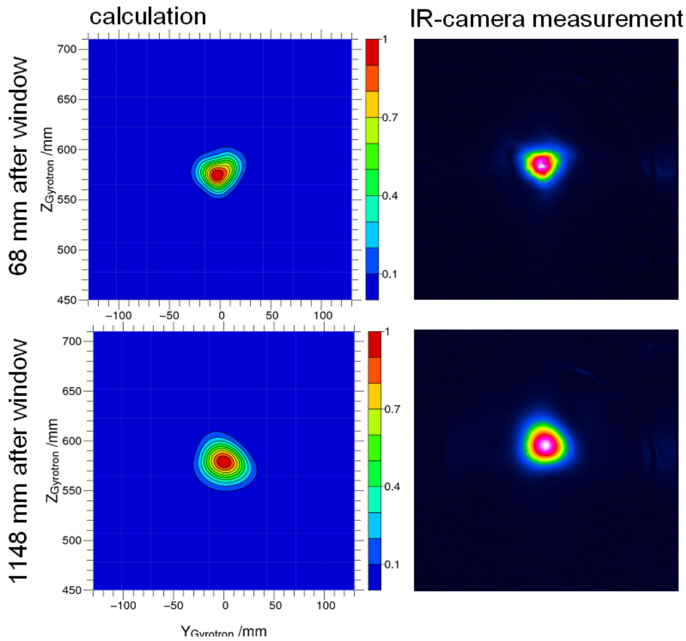


Fig. 4. Calculations (left) and high-power IR-camera measurements (right, with the same scales) of the mm-wave beam profile for the gyrotron operation at 0.17 THz in the $TE_{34,19}$ mode.

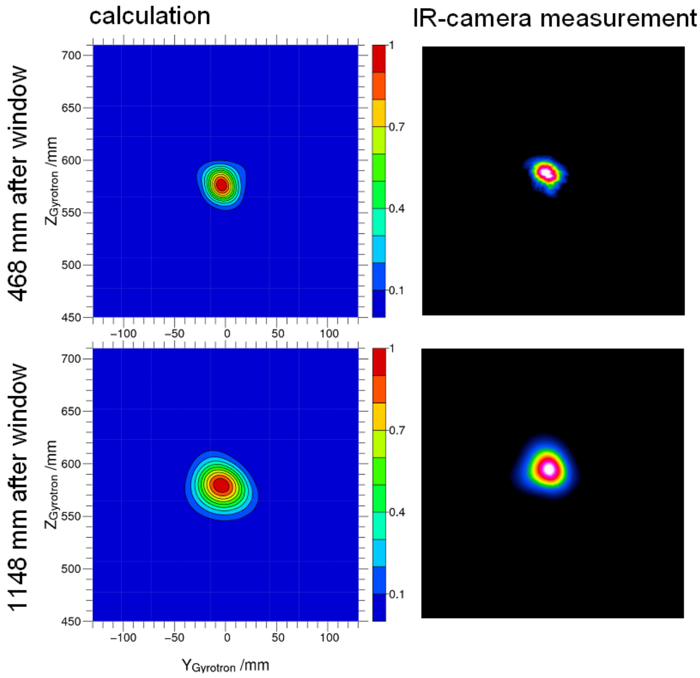


Fig. 5. Calculations (left) and high-power IR-camera measurements (right, with the same scales) of the mm-wave beam profile for the gyrotron operation at 0.1433 THz in the $TE_{29,16}$ mode.

Recently the gyrotron output window has been replaced by a broadband silicon-nitride Brewster window (supplied by NIFS in Japan) in order to be able to study the excitation of additional modes in the frequency range between 0.13-0.17 THz. The capability of multi-frequency operation of the gyrotron could have significant advantage in application both for plasma heating and suppression of plasma instabilities in a fusion reactor [12]. Simulations have shown that the q.o. output coupler with the new launcher has a good conversion efficiency for a number of modes between 0.13 and 0.17 THz [13]. In first experiments the excitation of modes around 0.14 THz has been investigated. The measurements have been concentrated on the excitation of the $TE_{28,16}$ mode at 0.1413 THz. The achieved results are promising with respect to the generated mm-wave power and efficiency as shown in Fig. 6.

As shown in Fig. 6 an output power of 1.8 MW with an efficiency of 26 % has been obtained in the $TE_{28,16}$ mode at 0.1413 THz. In addition, in the $TE_{29,16}$ mode at 0.1433 THz (the next azimuthal neighbor) an output power of 1.25 MW with 23 % efficiency has been generated. The measurements of the intensity profile of the mm-wave output beam with an infrared camera have confirmed the simulations (SURF3D [14,15]) resulting in a very good efficiency of the new quasi-optical output coupler also for the $TE_{28,16}$ mode at 0.1413 THz and the $TE_{29,16}$ mode at 0.1433 THz (Fig. 5).

The measured output powers in these experiments were limited by the vacuum conditions, which could not be further improved due to lack of time. Since in simulations for all investigated modes output powers above 2 MW have been found, a further increase in measured powers in the coming experiments is expected.

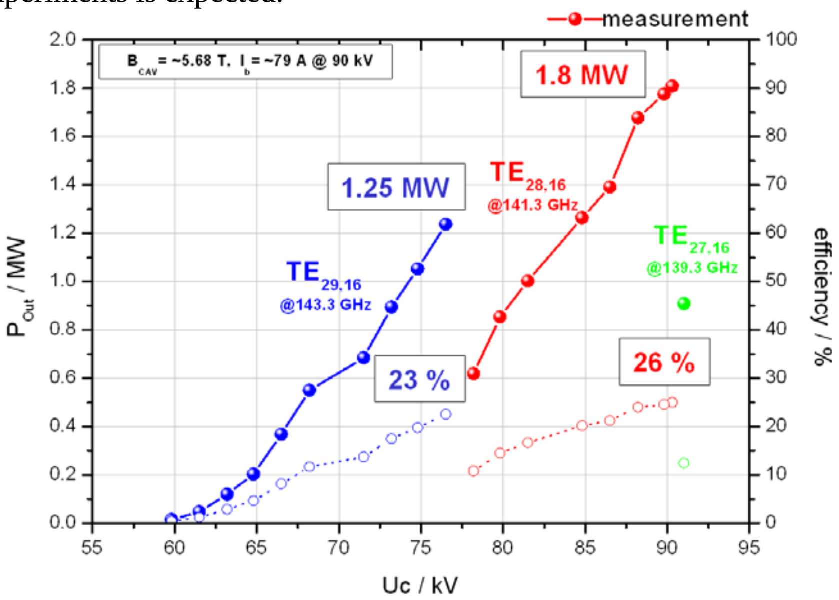


Fig. 6. Measured output powers and efficiencies vs. cathode voltage during frequency-step tunable operation in the $TE_{28,16}$ mode at 0.1413 THz and the $TE_{29,16}$ mode at 0.1433 THz.

## 4. Summary and Conclusions

Significant progress and improvement have been obtained in recent investigations on the short-pulse 2 MW, 0.17 THz coaxial-cavity gyrotron at KIT. Parasitic high-frequency oscillations observed in the frequency band from 0.15 to 0.16 THz have been eliminated by improving the beam tunnel. The modification consists mainly in a destruction of the azimuthal symmetry by introducing irregular longitudinal corrugations in the copper rings in order to suppress weakly damped circular electric modes. A result of these changes was a considerable improvement of the stability of single-mode operation. The increase of the cavity magnetic field to the nominal value of 6.87 T by using an additional normal conducting coil allows to operate the pre-prototype tube at the same parameters as the industrial CW gyrotron. At the nominal conditions a record output power of 2.2 MW with an efficiency of up to 30 % (without depressed collector) has been achieved. Up to now the short-pulse pre-prototype gyrotron has been equipped with a fused-silica vacuum barrier window which absorbs 3.3 % of the generated mm-wave beam power. With a synthetic diamond window, as required and foreseen for the industrial CW gyrotron, the output power would have been 2.3 MW at 31 % efficiency which is even more above the specified value of 2 MW. Employing a single-stage depressed collector (SDC) the efficiency will be raised above the specified value of 50 %.

During the operation with a novel q.o. output coupler, based on a newly designed launcher, excellent quality of the mm-wave output beam (Gaussian content of almost 96%) has been obtained. The amount of stray radiation losses inside the tube is reduced in comparison to the previous output coupler. The modified beam tunnel and the novel q.o. output coupler will be integrated into the refurbished industrial European CW prototype gyrotron for ITER manufactured by TED. This tube will be tested at CRPP Lausanne starting August 2010.

An efficient operation of the pre-prototype gyrotron at several frequencies and corresponding operating modes has been demonstrated. In particular, in the $TE_{28.16}$ mode at 0.1413 THz an output power of 1.8 MW with 26% efficiency has been generated and in the next azimuthal neighbor, the $TE_{29,16}$ mode at 0.1433 THz an output power of 1.25 MW with 23% efficiency has been obtained. These results have not been experimentally optimized because of lack of time and can be further increased – simulations predict output powers above 2 MW for a variety of frequencies between 0.13 and 0.17 THz (even 0.21 THz, if the corresponding magnetic field would be available). The quality of the mm-wave output beam has been very good for both modes. Besides other investigations, it is planned in the coming experimental campaigns to further study the operation of the pre-prototype gyrotron at different frequencies. The mm-wave output beam patterns generated with these modes will be measured, and a further increase of the output power above 2 MW is expected.

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