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Experimental results and recent developments on the EU 2 MW 170 GHz coaxial cavity gyrotron for ITER

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Abstract. The European Gyrotron Consortium (EGYC) is responsible for developing one set of 170 GHz mm-wave sources, in support of Europe's contribution to ITER. The original plan of targeting a 2 MW coaxial gyrotron is currently under discussion, in view of essential delays and damages. This paper reports on the latest results and plans with regard to the two 2 MW gyrotron prototypes, the industrial prototype at CRPP's CW test stand and a modular pre-prototype at KIT. The industrial prototype was delivered to CRPP end of September 2011 and reached an output power of 2 MW at an efficiency of 45 % and with good RF beam pattern, in only four days of short pulse RF test. These results validated all design changes made in reaction to the results of the experiments in 2008. On the fifth experimental day, an internal absorber broke, terminating any further experiment with this tube. In parallel, design and experimental activities at KIT went on, in particular featuring reduced stray radiation down to 4% of the RF power. Next years' plans for the 2 MW modular pre-prototype foresee a stepwise increase of pulse length.

1 Introduction

The ITER fusion facility which is currently under construction in a world-wide collaboration will be equipped with a powerful electron cyclotron resonance heating (ECRH) system, among others. It will generate 24 MW of mm-wave power at 170 GHz. Europe will provide for this purpose gyrotrons for a total of 8 MW generated power, which are under development through the European Gyrotron Consortium (EGYC), with Thales Electron Devices (TED), Velizy, France as industrial partner [1]. The original plan targeted four 2 MW coaxial cavity gyrotrons, to be developed using a modular short pulse pre-prototype at KIT and a series of three industrial CW prototypes, aiming at pulse lengths of 1 s, 60 s and one hour, respectively. Only the first CW prototype was built, delivered in 2008, and strongly modified and refurbished after the first experiments were not satisfying [1].

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This refurbished prototype was delivered to CRPP with major delays due to manufacturing problems in September 2011. It was shortly tested with good success, but the experiments were terminated by an internal RF absorber, which broke and flooded the tube with water, thus rendering the tube unusable. In view of this accident and the delays, and in view of the large experience in Europe with series production of conventional MW-class gyrotrons, a fallback to a conventional 1 MW 170 GHz gyrotron is currently under consideration. This discussion and the details of the 1 MW fallback development, which was already started in 2008, are outside the scope of this paper. The paper reports on the latest results with the two 2 MW coaxial gyrotrons, the refurbished prototype at CRPP and the short pulse pre-prototype at KIT (see Figure 1), as well as on the planning for further steps.

Fig. 1. Coaxial 2.2 MW 170 GHz short pulse pre-prototype gyrotron at KIT (left); the refurbished industrial long pulse prototype at delivery end September 2011 (mid); and the same prototype, installed at the CRPP test stand inside the ASG magnet (right).

2 Experimental results on the industrial prototype at CRPP

The refurbishment of the industrial prototype for the ITER gyrotron was started in 2009 and aimed at delivery to CRPP Lausanne in summer 2010. Due to various delays, the delivery date had to be shifted and took place finally at end of September 2011. Several manufacturing problems can be attributed to the attempt to refurbish such a large device, like leaking brazings and breaking of ceramics during bakeout. It should be noted that the refurbishment of the mirror box, containing the RF absorbers which finally caused the fatal damage, was considered critical by the manufacturer, after a first of the RF absorbers became untight at bakeout and had to be removed.

However, the prototype could finally be closed and baked in a careful procedure at lower temperature, but still arrived at delivery with a small leak in the gun region. This leak was sealed by resin, such that the gyrotron could be pumped, conditioned and tested.

2.1 Site acceptance test

Despite the small leak mentioned above, conditioning was fast and easy, resulting in very good vacuum conditions. The site acceptance tests (checks of vacuum properties, beam extraction, cooling capabilities and high voltage standoff) were all passed. The high voltage standoff was a problem for the former gun design when magnetic field was applied, due to formation of potential traps [2]. It was therefore a major success and validation of the new gun design and the applied new design principles, that the high voltage standoff with and without magnetic field was excellent, exceeding specifications (above 110 kV). Furthermore, the inner conductor of the coaxial cavity could be aligned with the satisfactory accuracy of 0.06 mm. The overall tube alignment was also crudely checked with success, by checking the behaviour of body current related to beam misalignment, which can be controlled through dipole coil currents in the CRPP and KIT magnets. This check was unfortunately only done in one direction, defined as x coordinate.

After the tests were successfully passed, the tube was accepted and green light to proceed with RF tests was given by TED on December 2nd 2011.

2.2 RF tests

RF tests started on December 5th and ended on the 9th due to an unrecoverable damage. Still, within these four days of operation the tube showed excellent potentialities. It was possible to reach nominal parameters (90 kV, 75 A) and extract 2 MW of output power with an efficiency of 45% (with single stage depressed collector) in the right mode. Pulse lengths were limited to about 1 ms. It should be noted that no particular optimization other than the magnetic field value was done, in particular the depression voltage was arbitrarily set to 30.5kV – at the nominal 35 kV, the efficiency would have exceeded 48%. Further optimization appeared easily possible (see Figure 2).

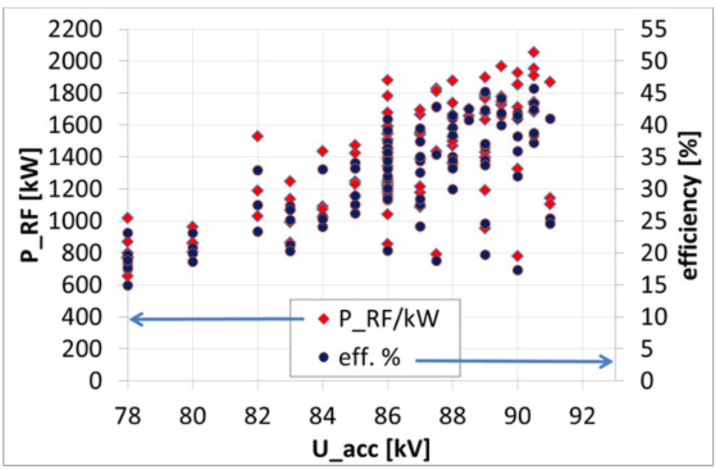

Fig. 2. RF output power and efficiency of the industrial prototype for different magnetic field settings.

Next important result was the confirmation of good performance of the new launcher, which already had been tested in the KIT pre-prototype in 2009 [3]. Even though the abrupt termination of tests disabled a precise measurement, the paper burn pattern of the RF beam on the window indicates a good beam shape with high Gaussian content and good positioning (Figure 3).

In addition, another problem of the former experiment disappeared: No low frequency oscillations were found, which may again be attributed to the revised electron gun design. Finally, there was also no indication of parasitic RF oscillations, which can be taken as another confirmation of the corrugated beam tunnel concept [4]. In summary, it can be said that all modifications applied to the prototype during refurbishment were validated to a high degree.

Some other observations were less positive or at least unclear: Already during site acceptance test, an unexpectedly high, but not prohibitive body current was observed. This could be related to a similar observation at the pre-prototype tests and will be discussed there. Then, during RF tests very high starting currents in the 60 A region were observed, while the onset of oscillations would rather be expected around 10A. At the same time, it turned out to be more difficult than usual to avoid operation in the wrong mode rotation. One hypothesis for further investigation is that such effects could have been caused by misalignment between tube and the magnetic field axis (see next section).

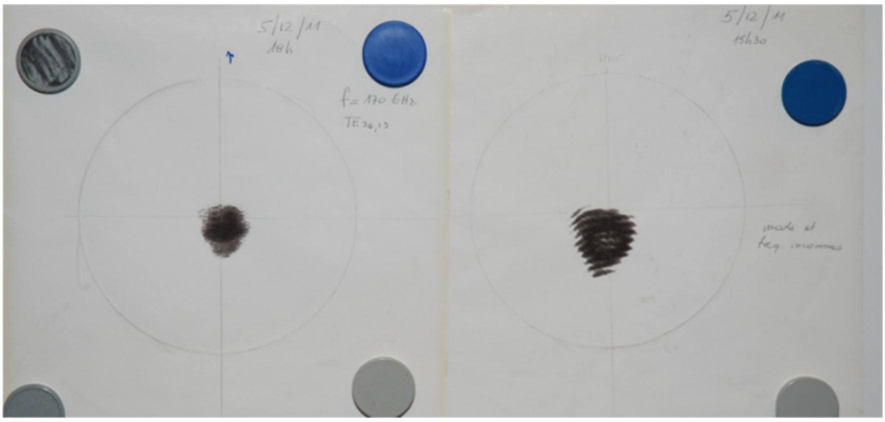

Fig. 3. Paper burn RF beam pattern of the industrial prototype at the RF window for $TE_{34,19}$ (left) and $TE_{35,19}$ (right).

From start of the tests on, some short acoustical noise could be heard when the wrong mode rotation appeared. This was attributed to the high internal stray radiation that is created in this case. The sounds could be produced through a shock wave in the water cooling inside ceramic absorbers. Finally, on the fifth RF test day, an internal absorber broke during an accidental, but not uncommon wrong rotation operation, which flooded the whole gyrotron with water. This is a total damage which permits no further refurbishment.

2.3 Evaluations after the experiment

Since the experimental data taken in these four days of operation is quite limited, the main post-experimental evaluation is the inspection of the damaged gyrotron. The most important question would be if the absorber was breaking due to stray radiation overload – which appears obvious, but would on the other hand not be expected in 1 ms pulses – or if any traces of pre-damage could be seen. These investigations are underway at TED.

Since the alignment of the magnet could not be checked due to lack of time before the experiment, this investigation was done afterwards, with two results. First, it was found that the magnetic axis was in fact misaligned by 0.7 mm in *y*-direction. This is particular unfortunate since the alignment check using the displaced electron beam was done only in *x*-direction, assuming it could be completed later. But in addition, it was found that due to some loose stabilisation structure the tube could be easily bent, by millimeters in the gun region. It means that the internal alignment of the gyrotron was finally determined by the position of the oil tank around the gun connectors, which is not well defined. In conclusion, it can be said that the tube alignment in *y*-direction in these experiments could have been anything between perfect and very bad, while the *x*-direction and the inner conductor alignment had been checked to be good.

3 Experimental results on the short pulse pre-prototype at KIT

In parallel to the industrial tube refurbishment, the experimental program with the modular short-pulse gyrotron at KIT is ongoing. It was necessary to refurbish the worn-out electron gun, and this opportunity was utilized to make it more similar to the prototype gun, for increased relevance of comparisons. In particular, the anode was designed with a halo-shield as in the prototype. At the same time, the whole gyrotron housing was reworked to fit into a 220 mm bore whole, to be compatible to other tubes and to gain space for an additional cooled normal conducting coil, thus achieving nominal B-Field of 6.87 T in CW in the Oxford Instruments magnet at KIT (see Figure 4). This modification also permitted the introduction of isolation to enable depressed collector operation. Finally, the prototype's launcher which was successfully tested before was further improved by smoothing its surface [5].

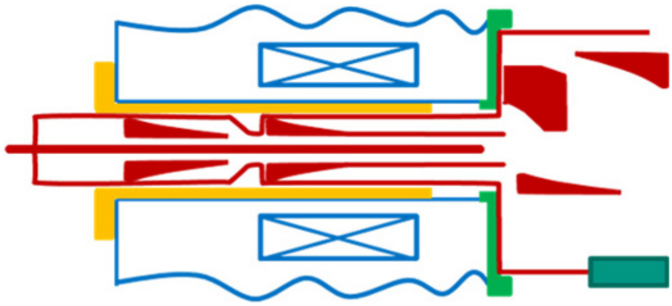

Fig. 4. Sketch of the KIT pre-prototype gyrotron with small gyrotron body inside the magnet (rotated; right side is the gyrotron's top). The orange shape is the cooled NC coil inside the magnet (blue), and the green thick material at the upper magnet end is a new isolating spacer that shifts the gyrotron in the right position and also enables depressed collector operation with high voltage standoff.

This experimental campaign is still running. One of the major achievements yet is to reach again high output power at good efficiency: 1.9 MW at 28 % efficiency was reached without depression yet, but the conditioning is still ongoing. Tests with depressed collector are also in preparation.

The most important result of this measurement campaign yet is a careful determination of stray radiation from the smoothed launcher. The stray radiation is now measured as 4 % of the RF power, to be compared to 7 % for the unsmoothed launcher and 5.5 % for a dedicated design done by the Institute of Applied Physics, Nizhny Novgorod, Russia. The Gaussian content of this new quasi-optical system is not determined yet, but also appears high in the thermal images taken (Figure 5).

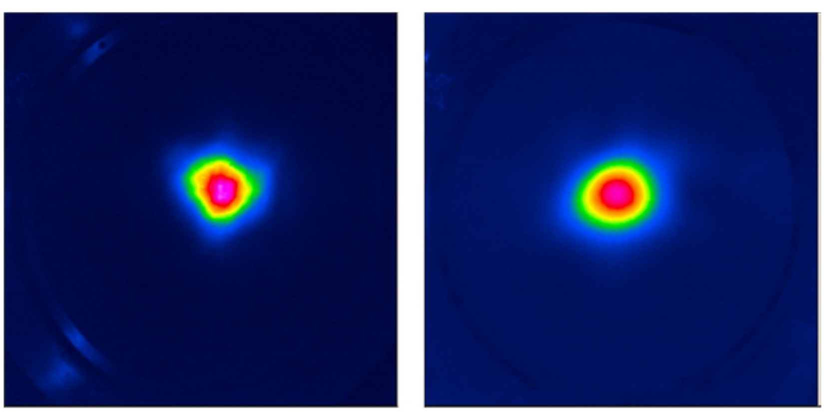

Fig. 5. Thermal image of the RF beam measured at the pre-prototype with smoothed launcher at 85 mm distance from window (left) and 1000 mm (right).

A less fortunate observation is an unexpected body current. It could be determined to be at the halo shield, indicating that the electron beam has some current portion at 1.8 mm higher beam radius. For this experiment, the body current can be avoided by changing the gun coil settings. However, the reason for this current, which might be related to electrons trapped between the cathode and the magnetic mirror, needs to be understood, and maybe the halo shield concept needs revision. In addition, strong low frequency oscillations around 100 MHz are seen during startup. These could be related to the electron gun's rear part, since this gun showed such oscillations before. The conclusion is that, while the prototype gun did not show any oscillations, such effects still need a deeper understanding. In electron gun design, it is clear now that the complete inner structures including the rear gun part need to be designed carefully.

4 Conclusions and future plans

The experimental results gained from the refurbished 2 MW coaxial cavity prototype are twofold: On the one hand, the applied design modifications were validated to a high degree, and the majority of the scientific goals were met despite the very short experimental time. On the other hand, the important goal of reaching long pulse operation (1 s) and demonstrating the cooling capabilities necessary for CW operation was not met and could only be investigated with a new 2nd prototype. The design changes for such a prototype are clear, the main change would be a revised internal RF absorber scheme, or the introduction of relief windows. Nevertheless, due to the major delay the decision about the further development goals of the EU ITER gyrotron development is currently pending.

In view of its future relevance, KIT will continue the experimental work on coaxial cavity gyrotrons. The current short pulse experiments are foreseen as a first step towards longer pulse lengths in a more modular approach. While the next experimental session will concentrate on further short pulse tests of different internal components, the subsequent step will be to replace collector and RF window by a large CW compatible collector and a CVD window, respectively. This aims at permitting operation in single pulses up to 100 ms. To finally reach second pulses and beyond, it is foreseen to upgrade and cool all remaining components to CW compatibility. The question how much modularity can be maintained in such a tube is under investigation and will be answered in the course of these tests.

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