NEW DESIGN OF THE GYROTRON USED FOR ECRH EXPERIMENTS ON TORE SUPRA

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For ECRH (Electron Cyclotron Resonance Heating) and current drive experiments on the tokamak Tore Supra[3], gyrotrons have been developed thanks to a collaboration between TED (Thales Electron Devices), Association Euratom-Confédération Suisse, Association Euratom-FZK and Association Euratom-CEA.
Limitations on pulse length (about 110 s) have been observed on the first series gyrotron during tests in Cadarache [2]. These limitations have been attributed to inadequate cooling and subsequent overheating of internal components in the tube. Moreover, the geometry of the launcher seems to be at the origin of spurious oscillations inside and at the output of the gyrotron, possibly leading to degraded performances.
To improve the gyrotron, new studies involving the same partners have been undertaken and a new tube has just been manufactured by TED, with the main modifications being the introduction of a new cooling system and a launcher with a different geometry. The factory acceptance tests were completed in January 2004 ; the gyrotron is now installed on the Cadarache test bed where long pulse tests(up to 600 s) will begin by mid June.

1. INTRODUCTION

In accordance with the long pulse objectives of the Tore Supra Tokamak, an ECRH system planned to inject 2.4 MW for a pulse length up to 600 s at the frequency of 118 GHz is presently under construction at CEA Cadarache. The generator will be made of 6 gyrotrons developed through a collaboration between TED, Association Euratom - Confédération Suisse and Association Euratom – CEA, with technical support from Association Euratom – FZK. Two tubes are already installed : the prototype and the 1st series gyrotron. The main specified parameters of the gyrotron are given in table 1 and a complete description of the whole system is available in [1].

Table 1 : Main parameters of the TH 1506B gyrotron			
Output power @ pulse length	500 kW @ 5 s 400 kW @ up to 600 s	Frequency	118 GHz +/- 300 MHz
Output signal	Gaussian beam	Window	Sapphire
Beam current	22 A	Mode purity at window	95.8 %
Electronic efficiency	33 %	Cavity mode	TE 22,6
Cathode Voltage	81.5 kV	Anode voltage	25 kV
Gun type	Triode MIG	Collector type	Conventional

2. LONG PULSE TESTS ON DUMMY LOADS

Both prototype and 1st series gyrotrons have passed the factory acceptance test (500 kW during 5 s) and have been delivered to the CEA for final acceptance tests (long pulse capability). The prototype reached 15.5 s at 400 kW and despite the specifications not been fulfilled, a record pulse of 300 kW for 110 s was achieved with the 1st series tube. This pulse was limited by strong degassing within the gyrotron. The pressure increase was observed during all the long pulse tests performed on this gyrotron even following extensive conditioning [1]. Meticulous examination, measurement and simulations [2], have shown the principal cause of the limitations to be inefficient cooling of the mirror tank. This was confirmed by calorimetric measurements, in which a power of 10 kW was seen to be dissipated in the mirror tank, probably concentrated in hot spots. In thermal simulations performed to analyze the behaviour of the mirror tank, assuming that the 10 kW previously measured are uniformly deposited on its internal surfaces (which is a rather optimistic assumption), the simulated temperature reaches a value comparable to the bake out temperature after 60 s and the evolution of the calculated temperature of the cooling water is very similar to the measured one.

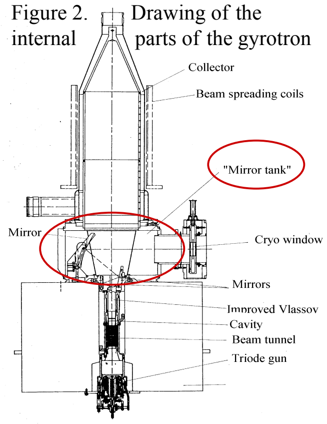


Figure 2. Drawing of the internal parts of the gyrotron

These first results explain the strong degassing which was seen during the experiments [2].

To attempt to find the reason for the excessive losses in the mirror box, spectrum analyser measurements were made : The arc detector located in the Matching Optics Unit (MOU) at the output of the gyrotron was taken out and replaced by a microwave horn, connected to a spectrum analyser through a mixer. The operating frequency of 118 GHz was observed, with the expected frequency shift of about 300 MHz due to dilatation of the cavity during the first 500 ms of each pulse. In addition this experiment showed spurious oscillations generated during the 5 s pulses (see figure 3). The main spurious oscillation which was always measured at 119.76 GHz showed hardly any frequency shift, which means that this mode is not generated in the cavity. Another frequency of 116.68 GHz was often measured as well. These spurious modes may be responsible for the overheating of the mirror box.

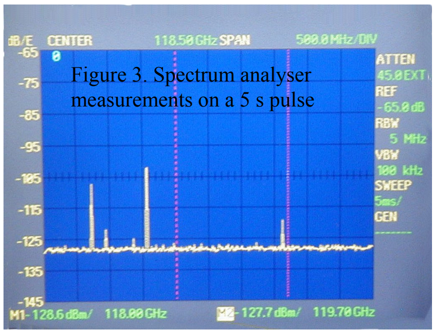


Figure 3. Spectrum analyser measurements on a 5 s pulse

Electromagnetic calculations on the injector show that, with a cylindrical shape as in the 1st series gyrotron, an electron beam may interact within the injector with a cavity mode at a frequency close to 119.7 GHz. A spurious TE 20,8,4 mode can therefore be generated in the injector (see figure 4) for some energy value of the electrons. This mode is characterized by ohmic losses of 20 kW and a radiated RF power of 8 kW (see figure 5), which can propagate to the mirror box, where localised absorption may create hot spots.

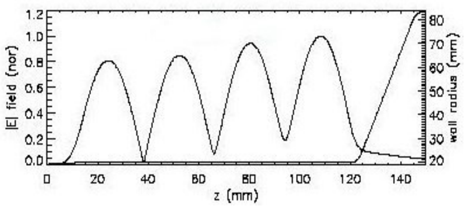
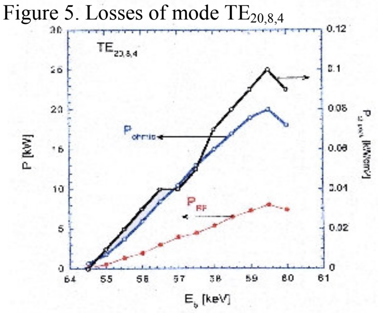


Figure 4. Mode $TE_{20,8,4}$ (frequency : 119.73 GHz) which is trapped in the injector

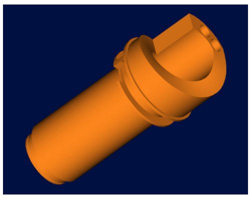
Figure 5. Losses of mode $TE_{20,8,4}$



3. NEW DESIGN OF THE GYROTRON

In order to improve the gyrotron, the following modifications have been made : The injector has been redesigned to eliminate the spurious oscillations and the cooling of all critical inner components of the tube have been improved.

The original cylindrical geometry of the launcher has been changed with the addition of a very small conical angle of 0.1° (see figure 6) : simulations show that spurious oscillations disappear when this conical angle is greater than 0.02°.



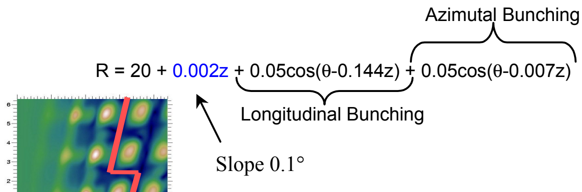


Figure 6. Characteristics of the new launcher

This conical shape was already validated with the 140 GHz gyrotron developed for the W7X experiment.
The other critical aspect is the prevention of heating of all the inner parts of the gyrotron. Various actions have been undertaken, beginning with a major improvement of the cooling system of the mirror tank : the previous tube had only a simple cooling circuit which was not implemented in the best place and was not efficient, due to the large thickness of the stainless steel wall of the box. The new cooling system is based on a double-wall structure with water flowing between the two walls. Moreover the ionic pumps which were placed inside the mirror tank and which have been observed to be strongly heated in the 140 GHz tube have been moved outside the box, with RF shielding in the conducts.
Furthermore, the bottom part of the collector is now made of stainless steel to enhance the RF absorption in this well cooled region, while all the internal parts around the mirror tank which are made of stainless steel and where the cooling could not be significantly improved have been coated with copper to reduce the RF absorption.

4. FIRST RESULTS

The factory tests which were completed in January - up to 500 kW and 5 s - have shown significant improvements :
First, the conditionning of the gyrotron was much faster than the previous tubes, with the working parameters, remaining well within the specifications ; the vacuum level during the 5 s pulses was better, even with a duty cycle of 10% (which was never reached neither with the prototype nor with the 1st series gyrotron).
Moreover, 7 kW have been measured by calorimetry too be deposited in the mirror tank cooling circuit, but with a short time constant (a few seconds instead of more than a hundred before the modifications) which

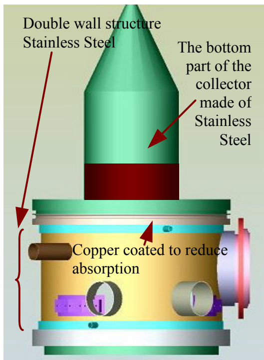


Figure 7. Modifications on the tube

proves the efficiency of the double wall cooling (see figure 7).
Calorimetric measurements have shown a reduction of the power deposited in the cavity-launcher from 45 kW to 25 kW, which seems to demonstrate the suppression of spurious oscillations thanks to the conical geometry of the launcher. This is confirmed by spectrum analyser measurements which show the absence of spurious frequencies in the band 118 GHz +/- 10 GHz at levels higher than –20 dB.
Nevertheless, a major problem has been detected during these factory acceptance tests through a mode purety analysis. The power density in the beam emitted from the gyrotron is measured at various distances from the window with an infrared camera, the RF waves propagating in air. Using a phase reconstruction program, the mode purety relative to a pure gaussian beam could be determined. Instead of a gaussian power distribution, the output beam is seen to contain two peaks, diverging at a constant angle of 1 or 2 degrees (see figure 8). This observation is still not well understood, but the problem seems to originate in the launcher inside the gyrotron.

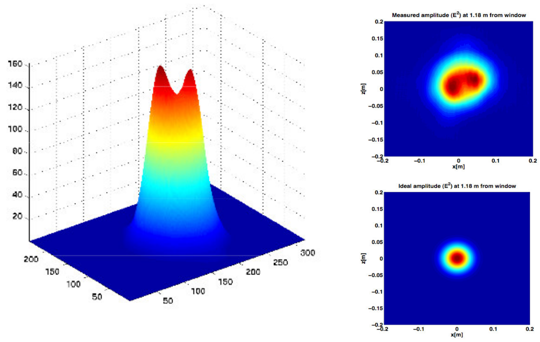


Figure 8. The 2 peaks measured in the output beam in 2D and 3D compared to what should be seen : a gaussian distribution.

One of the most serious consequences of the imperfect beam is the degradation in the coupling with the HE11 mode propagating in the waveguide. During the factory tests, excessive heating of the line lead to complete destruction of a pumping section in the line. This happened after several reliability test phases, each phase being composed of a hundred 5 s - pulses every 50 s. The good point is the absence of apparent degradation in the gyrotron.
A preliminary solution to allow us to proceed with testing of the long pulse capability of this gyrotron has been determined. This solution consists in modifying the curvature of the third mirror of the MOU in order to try to refocus the beam into a near-gaussian distribution at the entrance of the line to allow better coupling with the HE11 mode. Only the third mirror (see figure 9) could be modified because the other two are used to polarize the wave for plasma experiments.

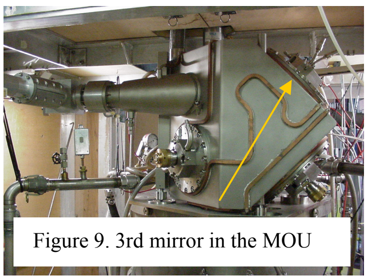


Figure 9. 3rd mirror in the MOU

This tube is now installed within the CEA facilities, on its test bed (see figure 10) and the modified third mirror has just been sent by TED. The tests will begin mid June, first on the same load used in the factory to allow us to evaluate the effect of the modification of the third mirror on the heating of the line.

Figure 10. New gyrotron being installed on the test bed

5. CONCLUSION

The analysis of the limitations which were observed on the 1st series tube have led to new studies and a new design of the launcher for the 2nd series tube and improvements on the cooling system. These modifications have been validated during the factory acceptance tests, but another problem has become apparent with regard to the output beam which is far from being gaussian. Hopefully, the modification made on the third mirror of the MOU should correct this problem and this gyrotron will be tested at CEA Cadarache from now and for a few months with the aim of reaching 400 kW, 600 s.

After validation of the new design, 5 other gyrotrons will be manufactured and delivered to Cadarache from mid 2005 to end 2006 in order to complete the ECRH system for Tore Supra.

REFERENCES

[1] "The 118 GHz ECRH experiment on Tore Supra", C. Darbos et. al. Fusion Engineering and Design 56-57, 2001, pp 605-609

[2] " Operation of the 118 GHz very long pulse Gyrotron for the ECRH experiment on Tore Supra ", C. Darbos et al. EC12, Aix-en-Provence, 2002

[3] " The ECRH/ECCD system on Tore Supra, a major step towards continuous operation ", M.Lennholm et al., Nuclear Fusion , Vol. 43(2003), pp 1458-1476