Status of the ECRH system on Tore Supra

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Abstract. An ECRH (Electron Cyclotron Resonance Heating) system capable of delivering 2.4 MW CW is presently under construction at CEA (Commissariat à l’Energie Atomique) Cadarache, for the Tore Supra experiment, to provide plasma heating and current drive by Electron Cyclotron Resonance interaction.

Due to some limitations observed on the first series tube which achieved 300 kW output power for 110 s, a new study carried out in a collaboration between TED (Thales Electron Devices), the Association Euratom-CEA and the Association Euratom-Confédération Suisse has led to the construction of a new modified gyrotron.

The new gyrotron, with a new launcher profile and a better cooling system is now installed in this test bed. A clear improvement in the time required to condition the tube has been observed. On the other hand poor mode purity in the output beam has resulted in the need to implement a cooling system for the waveguides transmitting the power to the dummy load. The gyrotron tests have been temporarily suspended while a new system for the automatic filling of the cryostats with liquid nitrogen and helium is being installed.

The experience gained from tests operations including some of the problems related both to auxiliary equipment and to the control of the gyrotrons will be presented with a special focus on long pulse related issues.

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. All the auxiliary equipment – Power Supplies, Control and Protection systems, Cryogenic and Vacuum Systems - has already been installed: the prototype and the 1\(^{st}\) series gyrotron are connected to the Tokamak (and have been used for plasma operation for several short experimental campaigns from 2001 to 2003) and the 2\(^{nd}\) series tube is on the test bed (In order to facilitate the acceptance tests of the gyrotrons and to make the tests independent of Tore Supra experiments, one of the six operating positions already prepared for the gyrotrons has been transformed into a dedicated
test bed). 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** | **Frequency** | **118 GHz +/- 300 MHz** |
| 500 kW @ 5 s | **Output signal** | Gaussian beam |
| 400 kW @ up to 600 s | **Window** | Sapphire |
| **Beam current** | **Mode purity at window** | 95.8 % |
| 24 A | **Electronic efficiency** | 33 % |
| **Cavity mode** | **Cathode Voltage** | 81.5 kV |
| **TE 22.6** | **Anode voltage** | 25 kV |
| **Gun type** | **Collector type** | Conventional |
| Triode MIG | |

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 (for testing long pulse capability). The prototype reached 15.5 s at 400 kW and a 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 after extensive conditioning. Meticulous examination, measurement and simulations[2], have shown the principal cause of the limitations due to an inefficient cooling of the mirror tank. This was confirmed by calorimetric measurements, which show a power of 10 kW to be dissipated in the mirror tank, probably concentrated in hot spots.

Electromagnetic calculations on the injector show that, with a cylindrical shape like 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 for some energy value of the electrons, depending on the working parameters used with the gyrotron. This mode is characterized by ohmic losses of 20 kW, and a radiated RF power of 8 kW which can propagate to the mirror box, where localised absorption may create hot spots.

This main spurious oscillation which was always measured (at 119.76 GHz), when the beam current reaches a value high enough to produce high frequency power, showed nearly no frequency shift, which means that this mode is not generated in the cavity. Another frequency of 116.68 GHz was often measured as well, but for lower beam currents. These spurious modes may be responsible for the overheating of the mirror box.

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 has been improved, following this simple rule: Each part which can be easily cooled is cooled...
and all the other parts are coated with copper, in order to reduce absorption, especially inside the mirror tank.

The original cylindrical geometry of the launcher has been modified with the addition of a very small conical angle of 0.1° (see figure 2) : simulations show that spurious oscillations disappear when this conical angle is greater than 0.02°. 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, 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 (where the heating was maximum) and was not efficient enough, 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 (see figure 3).

4. First results
The factory tests which were completed in January 2004 - up to 500 kW and 5 s - have shown significant improvements:

First, the conditioning 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 to 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 proves the efficiency of the double wall cooling.
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 purity analysis. The power distribution 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 purity 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 4). This phenomenon is still not well understood, but the problem seems to originate in the launcher inside the gyrotron.

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 led 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 resize 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 5) could be modified because the other two are used to polarize the wave for plasma experiments.

This tube was then installed within the CEA facilities, on its test bed and the modified third mirror has been placed inside the MOU. The tests began 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. Moreover, some parts of the transmission line were actively cooled.

Several temperature sensors (TS 2, 3, 4, 5, 6, 7, 11) have been located along the waveguides, in order to evaluate the thermalisation times and the decrease length needed to reach a temperature which could be acceptable (see figure 6). Tests have been performed with 500 RF pulses of 200 ms every 2 s.

The results (see figure 7) show that with the installation of cooling pipes around the guides, the maximum of the temperature is nearly reached after the 500 pulses whereas it is still increasing when the guides are not cooled, especially around the gate valve. The calorimetric measurements give a power of 8.2 kW dissipated in the cooling circuit.
Before connecting the gyrotron to the CW load, a test consisting in putting a 3 kW resistor inside a 1.2 m-long waveguide confirms the ability of the cooling pipes surrounding the guide to evacuate the heating of the line with a moderate temperature (about 60°C) at the surface.

The gyrotron was then connected to the CW load with a 15 meter-long transmission line which was actively cooled. The test were quickly stopped by an arc produced on the sapphire window. The origin of this arc is still unknown.

| TS    | Initial Temperature (°C) | Final Temperature (°C) | ΔT (°C) |
|-------|--------------------------|------------------------|---------|
| TS 5 (*) | 27.5                    | 39.6                   | 12.1    |
| TS 4   | 23.2                    | 34.8                   | 11.6    |
| TS 4   | 34.6                    | 40                     | 5.4     |
| TS 2 (*) | 26.3                    | 33.4                   | 7.1     |
| TS 3   | 22.5                    | 37.1                   | 14.6    |
| TS 3   | 36.6                    | 40                     | 3.4     |
| TS 6   | 30.4                    | 41                     | 10.6    |
| TS 6 (*) | 32.5                    | 45.9                   | 13.4    |
| TS 11  | 28.8                    | 65                     | 36.2    |
| TS 11  | 67.5                    | 85.6                   | 18.1    |
| TS 7 (*) | 28.8                    | 43.4                   | 14.6    |

(*): 650 RF pulses

Figure 7: Evolution of the temperatures

5. Conclusion

Regarding the manufacture of the next gyrotrons, the CEA needs to now quickly launch the series of 5 tubes; different options are available:

1. To keep the design of the last gyrotron, with the conical launcher, but with the double peak in the output beam, needing the cooling of the waveguides, which has not been tested in long pulses. The origin of this twin peak is still not known, but studies to understand this problem are going on.

2. To only keep all the improvements on the cooling system and the ionic pumps located outside the mirror box but to come back to the non-conical launcher, taken into account the parasitic oscillations in the working parameters of the gyrotron.

At the present time, some long-pulse tests are made on the prototype, in order to evaluate the consequences of the spurious oscillations inside the launcher; if after dozens of pulses of 40 s-length, no damage is observed on the gyrotron, the first option may be chosen.

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