Development of a 2-MW, CW Coaxial Gyrotron at 170 GHz and Test Facility for ITER

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Abstract. In ITER, EC heating and current drive (H&CD) is foreseen not only as a principal auxiliary system for plasma heating and as assist for plasma start-up, but is considered essential in meeting the key requirement of neoclassical tearing mode (NTM) stabilisation, by localized current drive. In the reference ECH design, ITER requires a total of 20MW/CW power at 170GHz using gyrotrons with a unit power of 1MW. A higher power per unit (2MW/gyrotron) would result in a strong reduction of the cost of the whole ECRH system, and would also relax the room constraints on the launcher antenna design. In view of the capability of coaxial cavity gyrotrons demonstrated with short pulse experiments at FZK, the European Fusion Development Agreement (EFDA) has started in 2003 the development of an industrial 170 GHz 2MW/CW coaxial cavity gyrotron, in a collaborative effort between European research associations CRPP/EPFL, FZK, TEKES and Thal’s Electron Devices (TED). The development plan includes three steps to reach successively 2MW/1s, 2MW/60s and finally 2MW/CW operation. The procurement of the first prototype is in progress and it scheduled to be delivered during the first quarter of 2006. The experimental tests of the prototypes will be carried out at CRPP/EPFL, where an ITER relevant test facility is presently under construction and will be achieved during the second half of 2005. The test facility is designed to be flexible enough, allowing the possible commissioning of tubes with different characteristics, as well the tests of the launcher antenna at full performances.
1. Introduction
In the ITER ECH Reference Design, it is foreseen to inject 20MW/CW of microwave power at 170GHz in the plasma, using gyrotrons with a unit power of 1MW. The main advantages of increasing the unit power of the gyrotrons for the electron cyclotron wave (ECW) system at ITER reside in a more flexible upper port launcher design and in an overall reduction of the installation costs. Coaxial cavity gyrotrons are serious candidates to reach such higher power levels since the inner conductor accumulates the positive effects of mode selectivity and a restriction of beam voltage depression. This matches the choice of a very high order operating mode, and a larger cavity radius in order to maintain the cavity peak ohmic load at a reasonable level (2kW/cm²). Based on short pulse proof of principle experiments carried out at FZK on a 165GHz tube, the European Fusion Development Agreement (EFDA) has launched a collaboration between European institutions and a commercial partner aiming at the development of a 2MW/CW/170GHz coaxial gyrotron. The years 2003 and 2004 were dedicated to a study to demonstrate the technical feasibility of a 2MW/CW tube. The development plan foresees to reach the CW regime in three steps: 2MW/1s, 2MW/60s and finally 2MW/CW operation. A contract between the EU and TED was placed by end of May 2004, for the procurement of the first prototype. Even though the target performances of this unit are 2MW/1s, it was designed to be fully compatible with CW operation.

In parallel to the gyrotron development, EFDA has placed a contract with CRPP to set up a test stand having the possibility to perform the tests and commissioning of the tube at full performances. It implies deep modifications of the existing infrastructure, the acquisition of new power supplies, the construction of a new dedicated 5-6 MW water cooling system as well as new control and data acquisition systems. The test stand is scheduled to be operative by end of 2005 in a temporary configuration where existing HV power supplies will be used instead of the new ones, the delivery of which will occur later in 2006.

Another contract between EFDA and FZK is running as well. The 165GHz short coaxial tube has been modified to operate at 170GHz, giving the possibility to the community to test the different scientific or technical options envisaged in a high power environment.

In this paper, we concentrate on the gyrotron design, with emphasis on different key aspects of the tube related to the high power and long pulse operation. The future test stand is then briefly described.

2. Gyrotron design
The design of the 170GHz/CW tube was largely based on the experimental results obtained on a 165GHz short pulse tube operated at FZK, which gave a proof of principle of the coaxial gyrotron ability to generate radiation in excess of 1MW at frequencies relevant to ITER. The dimensions of the existing tube as well as the magnetic field topology were used as a starting point for the design of the CW version.

The experience acquired during the development of the 0.5MW/118GHz/600s tube for CRPP and CEA, the 1MW/140GHz/CW for W7-X, was applied to the technical design in terms of options adopted for the cooling of different subassemblies, stray radiation handling and optimization of the RF output profile.

The main characteristics of the first prototype tube are summarized in table 1, and a sketch of the tube is given in figure 1.

A particular feature of the tube is that the RF structure (cavity, launcher, mirror system, mirror box) is at the depressed potential (+35 kV). Therefore, the use of an insulator between the tube and the superconducting magnet (SCM), as well as an insulating ceramic ring between the mirror box and the collector is necessary. A DC-Break will be placed between the gyrotron window and the next item (either the RF Conditioning Unit (RFCU) or an RF load).
2.1. Electron Gun

The coaxial magnetron injection gun (CMIG) assembly is shown in Fig. 2, together with the coaxial insert. At the nominal beam current, the emitting current density is of the order of 4.2A/cm². The electrodes have been shaped to limit the peak electric field at values < 7kV/mm. Preventing the possible built up of a Penning discharge, i.e. the trapping of electrons in regions with a defavorable magnetic field lines – equipotentials topology [1], was achieved by tapering the rear part of the cathode and the coaxial insert, with the additional beneficial effect of increased mechanical stability.

The electron beam characteristics at the nominal parameters were estimated using DAPHNE
Table 1. Main characteristics of the 2MW/170GHz/CW tube.

| Parameter                  | Value    | Parameter                  | Value          |
|----------------------------|----------|----------------------------|----------------|
| Frequency                  | 170 GHz  | Cavity peak losses         | 1.7kW/cm$^2$   |
| Magnetic field             | 6.86 T   | Cavity total losses        | 45kW           |
| Operating mode             | TE$_{34,19}$ | Insert peak losses     | .2kW/cm$^2$   |
| Cathode voltage            | -55 kV   | Insert total losses        | 2kW            |
| Body voltage               | +35 kV   | Stray radiation losses     | 100kW          |
| Beam current               | 75 A     | Window                     | CVD diamond    |
| RF output power            | 2 MW     | Window diameter            | 96 mm          |
| Power modulation           | 0.6 - 2MW| Window losses              | 880W           |
| Efficiency                 | 45%      | Collector loading (CW)     | 2.4MW          |
| Beam radius                | 10 mm    | Collector loading (modulated operation) | 3.1 MW |
| Velocity ratio             | 1.3      | Single-stage depressed collector | –             |
| Modulation frequency       | 5kHZ     |                            |                |

Figure 2. The electron gun and coaxial insert assembly.

[4] are summarized in table 2. The type of electron flow is intermediate, i.e. neither laminar nor non-laminar [5].

A parametric study of the electron beam parameters sensitivity on a possible placement inaccuracy of the superconducting magnet coils was performed in order to validate the magnetic field topology. Even though their nominal value is null, a proper choice of the gun coil currents (see fig. 1) can compensate for a ±0.5mm longitudinal shift of the bucking coil without any loss of quality. This is well with the mechanical tolerances.
Table 2. Electron beam characteristics obtained with DAPHNE at the nominal parameters \(I_b = 75\text{A}, U_{\text{cath}} = -55\text{kV}, U_{\text{body}} = +35\text{kV}, B_{\text{cav}} = 6.86\text{T}\. 

| Parameter                        | Value | Spread (rms value, % ) |
|----------------------------------|-------|------------------------|
| Beam radius \(R_b\), mm          | 10.00 | 1.29                   |
| Transverse velocity, \(\beta_\perp\) | 0.413 | 0.72                   |
| Axial velocity, \(\beta_\parallel\) | 0.317 | 1.21                   |
| Velocity ratio \(\alpha = \beta_\perp/\beta_\parallel\) | 1.30 | 1.92                   |
| Relativistic factor \(\gamma\)    | 1.171 | -                      |
| Beam depression, kV              | 2.6   | -                      |
| Magnetic compression ratio        | 34.5  | -                      |
| Current density at emitter, A/cm\(^2\) | 4.41 | -                      |
| Electric field at the emitter, kV/mm | 4.6  | -                      |
| \(E \cdot V\) at the emitter, kV\(^2\)/mm | 416  | -                      |

2.2. Coaxial Insert

This component is 1.2m long and shall be adjusted during operation with an accuracy of a few tenths of a millimeter with respect to the cavity wall using a 2D microactuator. The inner conductor alignment will be performed at reduced parameters by using a set of dipole coils in the gyrotron magnet. The required accuracy in the concentricity of the inner conductor to the cavity is 0.05mm. A mock-up coaxial insert made of Glidcop and stainless steel was realised to validate the assembling process. The design of the cooling circuit was improved to avoid turbulences giving rise to vibrations incompatible with a reliable and stable operation of the gyrotron. It will be performed by means of a coaxial water flow.

In addition, the structure was vibrated according to a road transport gauge. Potentially harmful resonances at frequencies of 22 Hz, 80 Hz and 160Hz were identified. Since the structure is relatively fragile, the coaxial insert support will be improved to give the possibility to lock its position during transportation.

2.3. Cavity

The cavity profile was designed in order to optimize the RF output, with the constraint of keeping the peak wall ohmic loading at an acceptable value of 1kW/cm\(^2\) (ideal copper at room temperature). The outer part consists in a linear input taper, a cylindrical section in which the interaction takes place, a linear output taper and finally a non-linear output taper which ensures that the power mode conversion of the TE\(_{34,19}\) to modes with a different radial index is < 0.2%. The beneficial effects of the coaxial insert are the minimization of the beam depression by fixing a potential close to the electron beam, and mode selectivity. The latter feature is even enhanced if the insert is tapered and if longitudinal corrugations are cut in it [2]. In the present case, the insert downtaper angle is 1 deg and it has 75 corrugations with a depth of the order of 0.44 mm. Multimode time-dependent simulations have shown that the nominal mode TE\(_{34,19}\) is dominant over a wide range of parameters. The effect of cavity thermal deformations was taken into account in an iterative procedure with the result that the position of the maximum of the electric field is shifted by 2 mm with no other major change.

Taking into account the Glidcop resistivity and a surface roughness factor of 1.5 (estimation based on thermal measurements on the 140 GHz gyrotron), it is estimated that the actual peak wall ohmic loading will be of the order of \(\rho_{\text{cavity}} = 1.7\text{kW/cm}^2\) (compared to 1kW/cm\(^2\) in the ideal case), corresponding to a total ohmic power dissipated in the cavity of 45 kW.
With the same arguments, the ohmic loading on the insert is expected to be of the order \( \rho_{\text{insert}} \approx 0.1 \text{kW/cm}^2 \) in the cavity, and the total losses on the insert \( \approx 0.4 \text{kW} \).

The cooling of the cavity will be performed by a diphasic cooling structure ('Rachig Rings'). A mock-up test has successfully shown the effectiveness of the cooling system, with a measured heat exchange coefficients as high as \( 0.15 \text{W/(mm}^2 \cdot \text{K)} \).

2.4. Dimple Wall Launcher and Quasi-Optical Mirror System

The mode \( \text{TE}_{34,19} \) is not ideal for conversion to a Gaussian beam and the edge diffraction losses of the conical dimple wall mode converter and quasi-optical mirror system were initially estimated to 10% of the RF output power. The key parameter in the optimization procedure of the launcher wall perturbations and the mirrors system was the minimization of edge diffraction losses at the cuts, around the mirrors and at the window [6]. The dimples combine \( \Delta m = 1, 2, 3 \) corrugations. The wall currents as a function of the longitudinal position and the azimuthal angle are shown in fig. 3, in 3dB steps down to -30dB. The red path corresponds to the location of the cut.

![Figure 3. Wall currents in the launcher, in 3dB steps. The red path indicates the launcher cut.](image)

The quasi-optical mirror system consists in three mirrors: (1) A quasi-elliptical mirror collects as much power radiated from the launcher as the room constraints allow and reflects a non-divergent wave beam. (2) The second mirror has a quadratic (toroidal) shape. (3) The last mirror has a non-quadratic surface contour optimized to maximize the Gaussian beam content at the window and to minimize window edge losses. The cost of minimization is a decrease of the beam quality.

2.4.1. Initial Quasi-Optical Mirror System

Two complete systems consisting of a dimple wall mode converter and a mirror system were built and tested at low power level (\( \approx 1 \text{ mW} \)) and at
high power on the modified FZK coaxial tube. Both results were coherent with each other, but exhibited a significant difference with numerical predictions. The discrepancy was attributed to the fact that the $\Delta m = 2$ launcher corrugations were mistreated when designing the mirror system. A proper handling of the launcher profile would allow the simulation to reproduce the cold and hot profiles [7].

2.4.2. Modified Quasi-Optical Mirrors System Correctly taking into account the $\Delta m = 2$ launcher corrugations, the shapes of the second and third mirrors were modified and will be cold tested soon. The computed power distributions at the window plane and 1m outside the window plane are shown in figs. 4 and 5 in 3dB steps.

![Figure 4. Power distribution in the window plane, for the improved mirror system, shown in 3dB steps.](image1)

![Figure 5. Power distribution 1m after the window plane, for the improved mirror system, shown in 3dB steps.](image2)

2.5. Internal Loads and Stray Radiation Handling

A particular care was brought to the handling of stray radiation inside the tube which is identified as the main issue toward the achievement of CW operation.

Internal water loads consisting in a water cooled ceramic tube will be placed inside the tube to evacuate efficiently trapped radiations. The advantage of internal loads with respect to a conventional relief window resides in the number of loads which can be accommodated in the tube, leading to a higher equivalent surface to evacuate stray radiation. Shown on fig. 6 is a pair of internal loads, and in fig. 7 the arrangement of 6 such loads in the tube.

The amount of stray microwave losses inside the gyrotron tube has been determined to be as high as about 8 % of the microwave output power. A test of internal microwave absorbers consisting of four water cooled $\text{Al}_2\text{O}_3$ tubes has been performed and placed inside the mirror box. It has been measured that the internal microwave load is absorbing a power of $0.022 \times P_{\text{out}}$ corresponding to more than 25% of the stray losses. High power tests are scheduled in the first trimester 2005 with the 140GHz/1MW gyrotron. The thermal limit of the component would be checked by placing the ceramic close to propagation axis of the RF beam. The vacuum reliability is also under investigation, with cyclic thermal heat treatments.
The mirror box itself has a double-wall structure and computations have shown that it can evacuate 100kW safely.

2.6. Window
The output vacuum window is made of a water edge-cooled CVD-diamond disk brazed to 96 mm clear aperture copper cuffs. A specific high temperature brazing process increases the reliability and simplifies the operating conditions without requiring anti-corrosion additives.

2.7. Collector
The collector is a critical component of the tube. During operation at full parameters, the loading will be of the order of 2.2 MW. During the first phase of the design, it was foreseen to have a coaxial design with the sweeping coils located in the central part. More accurate simulations conducted during the second phase have shown that this geometry would marginally allow the evacuation of the deposited energy, and have led us to abandon this option.

With respect to the first design phase [8], the collector diameter was increased to 600mm and the 6 sweeping coils are now external. The simulations have been refined to account for the eddy currents flowing in the wall, which have a shielding effect and prevent the magnetic field to penetrate into the collector [9]. The electron trajectories used to estimate the collector power deposition are taken from a self-consistent monomode simulation.

The simulations results indicate that it is possible to find a sweeping coils currents combination leading to a maximal peak power density $< 500 \text{ W/cm}^2$, showing that this is a usable collector design. Additional optimizations are nevertheless needed to make the peak power density less sensitive to a variation of the external parameters.

2.8. RF Conditioning Unit
The design of the RFCU was dictated by the need of flexibility. It consists in 5 mirrors located on an horizontal plane (see fig. 8. The first one (1) is planar and will be used to compensate for any misalignment of the gyrotron output beam. Two quadratic mirrors (2 and 5) will be used to match the beam to the HE11 mode of the transmission line while minimizing the peak power density on the universal polarizer made of two gratings (3 and 4). The alignment of such an in-plane arrangement is easy: mirrors 1,2 and 5 must be rotated around 2 axes, whereas the polarizer have only to be rotated around an axis normal to their surface.
In case the output beam profile at the window would lead to unacceptable edge diffraction losses and/or to a poor coupling to the HE$_{11}$ mode, it is envisaged to use a quadratic first mirror and synthetized mirrors 2 and 5. The RFCU cooling has been dimensioned to evacuate as much as 80kW.

3. Test Stand
It is foreseen to test the gyrotron tubes at the CRPP. A test stand, able to provide the electrical power, and with a 5-6 MW /CW cooling capability is being built and will be available for the beginning of the tests.

3.1. Electrical Power Supplies
A design study of the power supplies has been performed by different Associations as an ITER task. The electrical supply scheme is depicted in fig. 9

3.1.1. Long Term Power Supplies
The Main High Voltage Power Supply (MHVPS) fixes the cathode potential with respect to ground (55kV nominal, 60kV max.) and delivers the electron beam current (75A). Its shutdown time is 30$\mu$s. A PSM like (pulse step modulator) option has been retained.

The Body Power Supply (BPS, 40kV, 150mA static, <5A transient) is connected between the body and the grounded collector. It is responsible for the cathode to body potential regulation with an accuracy of $\pm$0.5%, and provides the modulation capability (25kV peak-to-peak) at frequencies up to 5kHz. The minimal modulation frequency is fixed by the maximal thermal loading that the collector can stand. The construction of the BPS will be PSM based as well. In order to limit the fault energy in the gyrotron to a value <10J in case of failure or arc, a High Voltage Solid State Switch (HVSSS), equipped with IGBT’s (Isolated Gated Barrier Transistor) will be used. Beyond the protective usage of this device, it can also be used to make on-off modulation of the electron beam (with the advantage that there is no collector loading during the off phase) at frequencies up to 5kHz.
3.1.2. Temporary Power Supplies (Plan B) The delivery of the above mentioned power supplies is scheduled approximately 9 months after that of the gyrotron and the SCM. During the first stage of experiments, an existing 85kV/80A power supply operated on the TCV ECRH system (RHVPS) will be used to perform the initial short pulse tests. Because of the relatively far location of the RHVPS ($\approx 100$ m from the tube), a crowbar is foreseen (see fig. 10). If desired, it might also be possible to use a BPS to reach the nominal accelerating voltage.

3.2. Cooling Set-Up
The cooling system has been designed to be compliant with the ITER DGR1 (Design Requirements and Guidelines Level 1): Nominal inlet temperature: $T_{in} = 40^\circ$, maximum outlet temperature: $T_{out} = 70^\circ$, nominal inlet pressure: $P_{in} = 6$bars. It will consist in three separate circuits dedicated to the collector, the auxiliaries and the RF load.
A view of the Test stand as it will appear is shown on fig. 11. The Test stand is scheduled to be ready for operation by end of 2005.

4. Present status and conclusion
A contract has been placed by the European Commission with TED for the production of the first one of three 2MW/170GHz gyrotron prototype. The target performance of the tube is 2MW/1s, but the design is CW compatible. The delivery is scheduled for the end of the first quarter 2006, approximately at the same time as the Superconducting Magnet. Due to the later delivery of the power supplies, existing ones will be temporarily used. The test stand infrastructure is being set-up and should be operative for end of 2005.

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