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Status of the development of the EU 170 GHz/1 MW/CW gyrotron

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ABSTRACT

The progress in the development of the European 170 GHz, 1 MW/CW gyrotron for electron cyclotron heating & current drive (ECH&CD) on ITER is reported. A continuous wave (CW) prototype is being manufactured by Thales Electron Devices (TED), France, while a short-pulse (SP) prototype gyrotron is in parallel under manufacture at Karlsruhe Institute of Technology (KIT), with the purpose of validating the design of the CW industrial prototype components. The fabrication of most of the sub-assemblies of the SP prototype has been completed. In a first step, an existing magnetron injection gun (MIG) available at KIT was used. Despite this non-ideal configuration, the experiments provided a validation of the design, substantiated by an excellent agreement with numerical simulations. The tube, operated without a depressed collector, is able to produce more than 1 MW of output power with efficiency in excess of 30%, as expected, and compatible with the ITER requirements.

1. Introduction

The European Gyrotron Consortium (EGYC) together with its industrial partner Thales Electron Devices (TED), Vélizy-Villaboublay, France and F4E is presently developing the EU 1 MW, 170 GHz cylindrical-cavity gyrotron for ECH&CD on ITER. The development was initiated in 2008 as a risk mitigation action during the development of the 2 MW coaxial-cavity gyrotron for ITER [1]. Since then, preliminary designs of the cavity [2] and the MIG [3] have been reported.

The technological design of the 1 MW gyrotron is similar as possible to the 1 MW, 140 GHz, CW Wendelstein W7-X gyrotron [4] making use of the experience gained during the manufacturing of the industrial series of already seven tubes. Same is valid for the principal scientific design [5]. However, the knowledge and understanding gained during the development of the coaxial-cavity gyrotron were taken into account for the design improvements of several subcomponents, e.g. the magnetron injection gun (MIG). More details about the gyrotron structure and the operating parameters of the tube are presented in Section 2.

Based on the project strategy developed by F4E, two prototypes are foreseen: (i) a single CW industrial prototype intended to reach the ITER requirements in terms of output power, efficiency, RF beam quality and pulse length, and (ii) a modular SP prototype intended to validate the design of the main gyrotron components in pulse length of few milliseconds.

The CW prototype is under manufacturing and the delivery is planned for 2015. The first phase of RF tests will be performed

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with the existing Oxford Instrument (OI) super-conducting magnet (SCM) at the KIT gyrotron test stand by the end of 2015 with a pulse length limited to 3 min due to high voltage power supply. In parallel, a new liquid Helium-free (LHF) SCM will be procured and delivered to the EU gyrotron test stand at EPFL-CRPP. Tests on the 1 MW, CW prototype will be extended to CW operation at EPFL-CRPP.

On the other hand, the fabrication of most of the components of the SP prototype has been completed and some preliminary experiments have been recently performed with the use of an existing coaxial-cavity MIG and a modified anode available at KIT. More details about the design and the fabrication status of the SP prototype are presented in Section 3, while the first experimental results are reported in Section 4.

2. Gyrotron structure & operating parameters

A three dimensional view of the CW prototype is shown in Fig. 1.

The key components of the gyrotron are as follows: (i) the MIG where the electron beam is generated, (ii) the beam-tunnel to suppress any parasitic oscillation which could be excited between MIG and cavity, (iii) the cavity in which the interaction takes place, (iv) the quasi-optical system (QOS) which converts the nominal operating mode into the linearly polarized fundamental Gaussian-like free-space mode, and finally the single stage depressed collector (SDC), which gathers the spent beam electrons. More details about the design of the key components of the gyrotron can be found in [5,6].

The nominal operating parameters of the gyrotron are given in Table 1. The operation of the gyrotron with a lower voltage operating point was also investigated to explore the capabilities of the

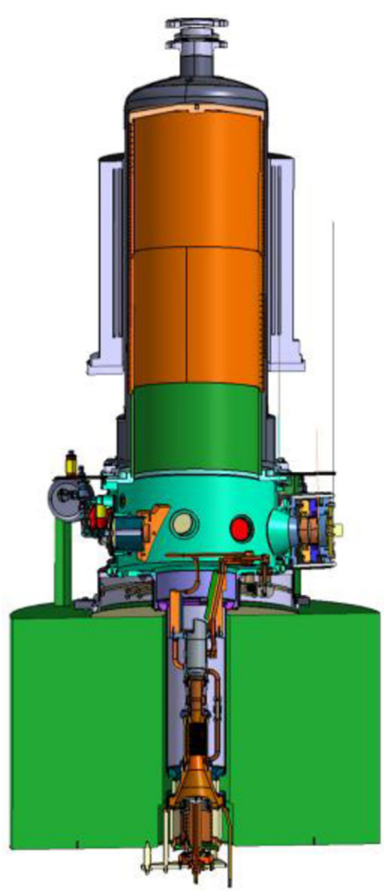

Fig. 1. Three-dimensional view of CW prototype.

Table 1
Gyrotron operating parameters.

Parameters	Nominal	Low voltage
Operating cavity mode	$TE_{32,9}$	
Magnetic field, B_0	6.78 T	6.69 T
Beam voltage, V_b	80 Kv	70 kV
Deceleration voltage, V_d	35 kV	
Beam current, I_b	40 A	45 A
Beam radius, R_b	9.44 mm	
Pitch angle, α	1.3	1.2

Table 2
Expected gyrotron performance.

Output power at RF window	1 MW
Operating frequency (cold cavity: 170.23 GHz)	170 GHz
Gaussian mode content	98.6%
Interaction efficiency	35%
Overall efficiency w/o SDC	32%
Overall efficiency with SDC	>50%
Internal losses (IL)	10.5%
Stray radiation (included in IL)	<4%

power supply specifications of ITER (see also Table 1). For both operating points, the expected gyrotron performance satisfies ITER criteria as shown in Table 2.

The efficient operation of the gyrotron at both operating points is possible due to the flexibility of the Oxford Instruments (OI) SCM available at KIT. The currents of the SCM coils are supplied by three independent power supplies (PS). This advantage provides the flexibility to generate magnetic field profiles with the following characteristics: (i) the appropriate value for the magnetic field at the cavity, shown in Table 1, (ii) the appropriate magnetic compression, in order to ensure that the electron beam radius at the cavity has the required value, as it is also shown in Table 1, and (iii) a large range of the magnetic field angles φ_B at the emitter and hence flexibility to adjust the average pitch angle α of the beam at the cavity

The magnetic field angle φ_B is a very important operating parameter due to the fact that it is the only way to adjust the pitch angle when a diode gun is used, as it is the case for the 1 MW EU gyrotron, while keeping constant all other operating parameters, such as the magnetic field at the cavity, the beam radius and the voltage. In particular, the pitch angle is affected by the variation of the magnetic field angle due to the fact that the initial transverse velocity $\boldsymbol{v_t}$ of the electron trajectories depends on the cross product $\boldsymbol{E} \times \boldsymbol{B}$ of the electric $\boldsymbol{E}$ and magnetic $\boldsymbol{B}$ fields on the surface of the emitter ring. A variation more than 8° of φ_B is possible with the OI-SCM, keeping the appropriate values for the magnetic field at the cavity and the magnetic compression. This range ensures a significant adjustment range for the pitch angle with a low velocity spread (smaller than 3%), as it is shown in Fig. 2. However the laminarity of the beam is also affected by the variations of φ_B, as shown in Fig. 3. For negative values, the beam is non-laminar, for positive values the beam is laminar, while for the nominal value $\varphi_B = 0$ the shape of the beam is at the boundary of the two states.

An additional parameter which should be taken into account in the gyrotron design and operation is the depression voltage at the cavity due to the space charge of the electron beam which in the cylindrical cavity gyrotron could have a significant value. The depression voltage for the EU gyrotron for ITER is of the order of 10% of the accelerating voltage. The MIG is optimized considering the possibility of to have some first experimental results using an available electron gun at KIT and to ensure modularity, with the full CW neutralization conditions, i.e. beam voltage is equal to the accelerating voltage. For the operation of the gyrotron in SP conditions a higher accelerating voltage is required for the compensation of the