Dual-frequency, 126/84 GHz, 1 MW gyrotron for the upgrade of the TCV EC-system

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***Abstract*—The TCV tokamak is presently undergoing major heating upgrades, installing a neutral beam for direct ion heating and increasing the electron cyclotron (EC) power injected in X-mode at the third harmonic (X3) and second harmonic (X2). The EC-system upgrade consists of adding two dual-frequency, 84/126 GHz, gyrotrons for X2 and X3 heating with a 1MW rf-power per gyrotron at both frequencies and 2s pulse length. The design of the dual-frequency gyrotron presented in this paper is based on the 140 GHz W7-X gyrotron and has been carried out within a European collaborative effort. A partial re-design of some internal components (triode-gun, cavity, QO-launcher and collector) allows to obtain powers in excess of 1 MW and a very-high gaussian content (>97%) at both frequencies without depressed collector.**

I. Introduction

THE X3 upgrade project [1] consists of adding two dual-frequency gyrotrons (126 GHz/84 GHz) with a total power of 2 MW at 126 GHz (for top-launch X3) or at 84 GHz (for low field side (LFS) injection X2) of 2 MW. The three existing gyrotrons operating at 118 GHz will be relocated to inject power from the LFS using the existing X2 transmission lines and launchers (Fig.1): single pass absorption in excess of 70% can be achieved even in this configuration in plasmas pre-heated by top-launch X3. Bulk electron heating with nearly full single-pass absorption will then be ensured by the 2 MW from the top launcher, while localized deposition necessary for MHD control will be possible with the 1.5 MW launched from LFS. The same transmission lines and power supplies presently used for top-injection of the 118 GHz gyrotrons will be used. Similarly, the same high voltage power supply will be used for either X2 or X3 LFS launch as required by the TCV experimental program.

II. Tube design

The gyrotron design is essentially based on modifications of the W7-X gyrotron [2-4] in which some sub-components have been redesigned using the most advanced models. The electron beam operating parameters have been chosen to be compatible with the existing power supplies, and the magnetic field profile provided by the W7-X tubes magnets has been scaled. The operating modes have been chosen such that their coupling to the electron beam is close to optimal, with frequencies (84 GHz and 126 GHz) as close as possible those of the existing tubes, with the additional constraint that their wavelengths should correspond to an integer number of half-wavelengths in CVD diamond. This resulted in the choice of modes $TE_{17,5}$ at 83.91 GHz and $TE_{26,7}$ at 126.16 GHz respectively.

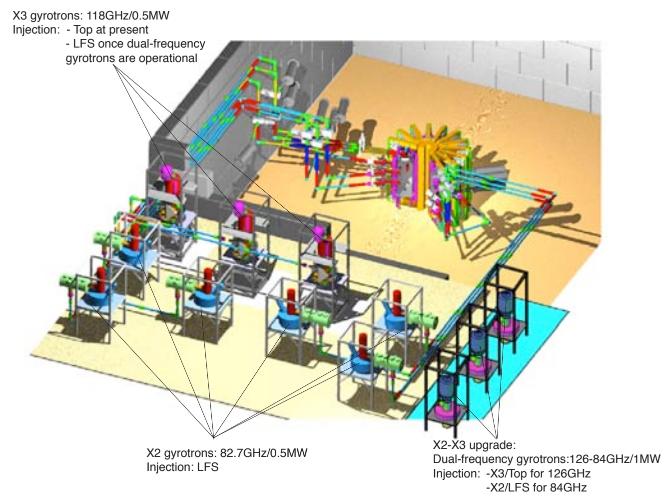

Fig.1. Layout of the foreseen upgrade of the TCV EC-system with the dual-frequency 1MW gyrotrons shown on the right.

The main redesigned component is the electron gun for which, instead of a diode gun (W7-X), a triode gun will be implemented in the dual-frequency gyrotron, providing the necessary flexibility in the range of achievable electron beam parameters at both frequencies. Starting from the W7-X electron gun geometry, the code ARIADNE [5] was used to optimize the electrodes shapes, taking into account recently added design criteria such as the absence of potential wells and the avoidance of trapped trajectories for electrons emitted from any part of the gun [6].

The gyrotron cavity underwent a very minor redesign essentially consisting in lengthening by 5mm the constant radius section in order to increase the quality factor and the efficiency at frequencies lower than the original one. Monomode and multi-mode time-dependent simulations using the code packages TWANG [7] and EURIDICE [8] were carried out to validate the mode choices and perform a fine tuning of the magnetic field. Results of the multi-mode computations are shown in Fig.2, in a realistic case where the time dependence of the beam parameters and a 16% rms spread in the velocity have been taken into account. They show that single mode operation with a diffracted power in excess of 1 MW at the operating voltage (78 kV) can be expected at both frequencies, with a stability range of 2-4 kV.

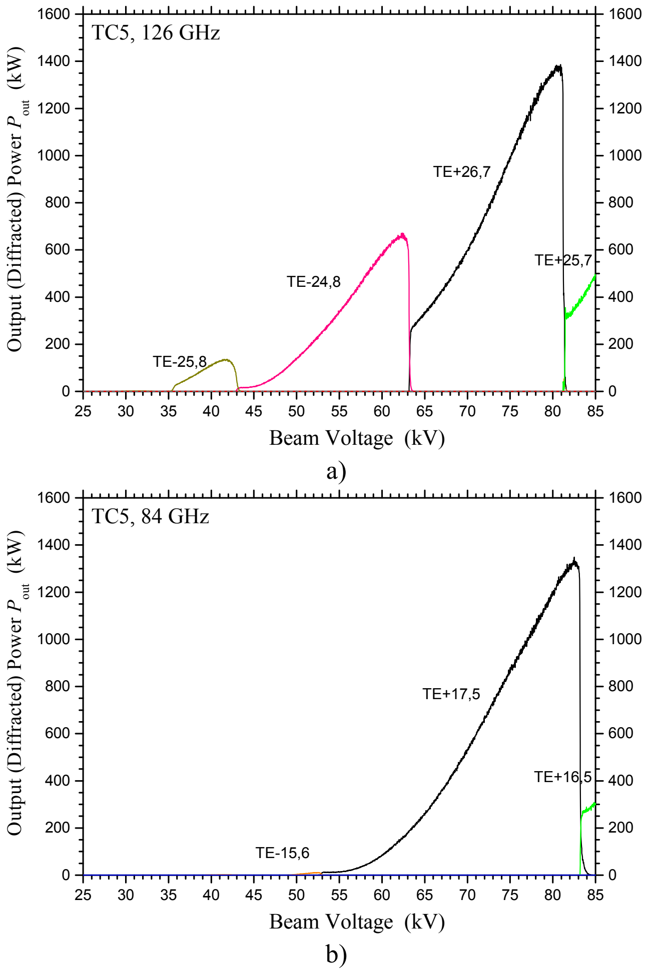

Fig.2. EURIDICE multimode simulations including the time dependence of the beam parameters and a 16% rms spread in the velocity. The beam current is 40 A, and the pitch factor is 1.3 in both cases. a) Mode $TE_{26,7}$ around 126 GHz, with B= 4.98 T, b) Mode $TE_{17,5}$ around 84 GHz, B= 3.31 T

In order to reach the highest Gaussian mode content, a significant effort has been placed in the redesign and optimisation of the launcher and the internal mirrors [9]. A satisfying compromise between the Gaussian content, the beam size and centering at the window and he beam waist location could be found and is illustrated on Fig. 3, where the field distribution for the mode $TE_{26,7}$ is shown with a linear scale. The beam waist is of the order of 20 mm and is located ca. 100 mm after the window. The results were cross-checked with SURF3D, which additionally estimated the stray radiation level to <4%. The matching optics to efficiently couple the output beam into a HE_{11} waveguide has still to be designed.

Based on the fact that on TCV only 2 s rf-pulses will be used, together with the constraint of using the existing high-voltage power supplies, it has been shown using advanced simulation models that the collector loading allows the operation without a depressed collector.

The gyrotron design parameters are summarized in Table 1. The tubes will be manufactured by Thales Electron Devices, with the first unit operational on TCV by end of 2017.

In parallel to the tube procurement, two new magnets will be procured. They will be based on the W7-X geometry, except that they will be characterized by an increased flexibility in the gun region that will allow us to optimize the field gradient around the emitter.

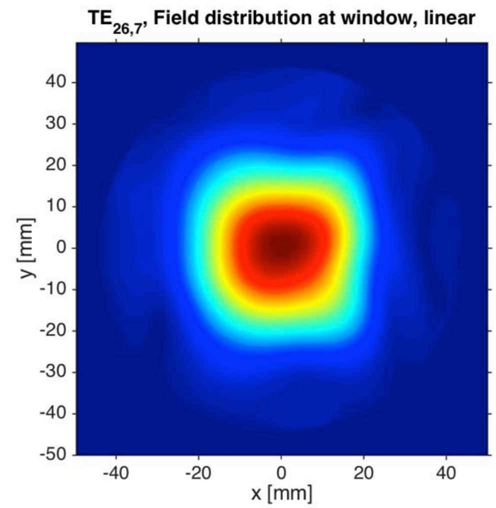

Fig.3. Field distribution at the window, mode $TE_{26,7}$. The estimated Gaussian content is 97.6% and the stray radiation level is estimated at 2.5%.

Operating cavity mode	$TE_{17,5}$	$TE_{26,7}$
Frequency [GHz]	83.91	126.16
RF output power [MW]	1.05	1.2
Cavity wall-loading [kW/cm^2]	1.1	2.1
Beam current [A]	40	40
Beam energy [keV]	78	78
Mod-anode voltage [kV]	-38	-26
Pitch angle, α	~1.3	~1.3
Cavity magnetic field, [T]	3.31	4.98
Electronic efficiency [%]	35	41
Gaussian content [%]	97.7	97.6

Table 1. Design parameters for the TCV dual-frequency gyrotron.

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