Recent Development of a 1.5 MW, 140 GHz Continuous-Wave Gyrotron for the Upgraded ECRH System at W7-X

Stefan Illy[1], Konstantinos A. Avramidis[1], Zisis C. Ioannidis[1], Gaetano Aiello[2], Patrick Bénin[3], Ioannis Chelis[4], Andreas Dinklage[5], Gerd Gantenbein[1], John Jelonnek[1], Jianbo Jin[1], Heinrich P. Laqua[5], Alberto Leggieri[3], François Legrand[3], Alexander Marek[1], Stefan Marsen[5], Ioannis Gr. Pagonakis[1], Tobias Ruess[1], Tomasz Rzesnicki[1], Theo Scherer[2], Dirk Strauss[2], Manfred Thumm[1], Ioannis Tigelis[4], Dietmar Wagner[6], Jörg Weggen[1], Robert C. Wolf[5], and the Wendelstein 7-X Team[5]

[1,2]Karlsruhe Institute of Technology (KIT), [1]Institute for Pulsed Power and Microwave Technology,
[2]Institute for Applied Materials - Applied Materials Physics, 76131 Karlsruhe, Germany
[3]Thales Electron Devices SAS (TED), Microwave & Imaging Sub-Systems, 78141 Vélizy-Villacoublay, France
[4]National and Kapodistrian University of Athens (NKUA), Department of Physics, 15784 Athens, Greece
[5,6] Max Planck Institute for Plasma Physics (IPP), [5]17491 Greifswald, Germany, [6]85748 Garching, Germany

***Abstract*—To increase the total injected Electron Cyclotron Resonance Heating (ECRH) power in the plasma of the nuclear fusion experiment Wendelstein 7-X (W7-X), an upgrade of the existing gyrotron installation is in progress. The existing ECRH system, currently equipped with ten one-MW-class, 140 GHz continuous wave (CW) gyrotrons, will be augmented by enhanced 1.5 MW tubes, which are based on the successful existing 1 MW gyrotron design.**

I. Introduction

Building on a highly reliable and powerful ECRH system, (delivering second harmonic X- and O-mode heating), unexpectedly good plasma performance (in terms of the highest triple product achieved for stellarators) and pulse lengths (up to 100s) were achieved even in the first experimental campaigns of the W7-X [1-3]. EC Current Drive has been demonstrated as an efficient tool to compensate the bootstrap current in the plasma [4]. In order to achieve high plasma β and low collisionality as expected in reactor scale devices, however, the presently installed, effective heating (~ 7.5 MW in the plasma) is too low and needs upgrades of the ECRH system. To this end, a prototype development of a 1.5 MW, 140 GHz CW gyrotron is initiated and planned to be followed by two series tubes. The associated power enhancement of the quasi-optical transmission line, required infrastructure and preparation of two additional gyrotron positions at W7-X are also ongoing.

II. Key Design Improvements

The design of the 1.5 MW CW gyrotron is an upgrade of the successful design of the existing 1 MW, 140 GHz gyrotrons at W7-X, combining risk mitigation and cost control [5]. The following changes and improvements will be incorporated to guarantee operation at 1.5 MW:

- Increase of the cavity diameter for operation in the $TE_{28,10}$ mode (instead of the $TE_{28,8}$ mode), while keeping the same electron beam radius. A typical multi-mode start-up scenario obtained for this cavity is shown in Fig. 1, indicating a sufficient margin for reaching the 1.5 MW power level.
- Adaption of the electron gun to permit higher electron beam current, while providing good electron beam quality [6,7].
- Improved cooling of the resonator (assuming a peak wall loading of approximately 2 kW/cm²).
- A mirror-line quasi-optical launcher [8] will be used (instead of the harmonically-deformed-wall type); the final (third) mirror of the RF output system will be adjustable. The theoretically expected Gaussian mode content at the window is 99.0 % with a stray radiation fraction of 1.65 %. Cold measurements of the full quasi-optical system have been already successfully performed showing a Gaussian mode content of 97.1 %. Figure 2 compares the calculated and measured profiles at the window plane, showing the good agreement.
- An advanced beam tunnel has been designed at NKUA, providing an alternative improved option for the 1.5 MW prototype. As in the original version for the 1 MW W7-X gyrotron, the beam tunnel consists of alternating stacked absorbing dielectric rings and indented copper rings; in the improved version the dielectric and diffraction losses of parasitic beam-tunnel modes are higher by 60 % to increase their starting currents [9-11].

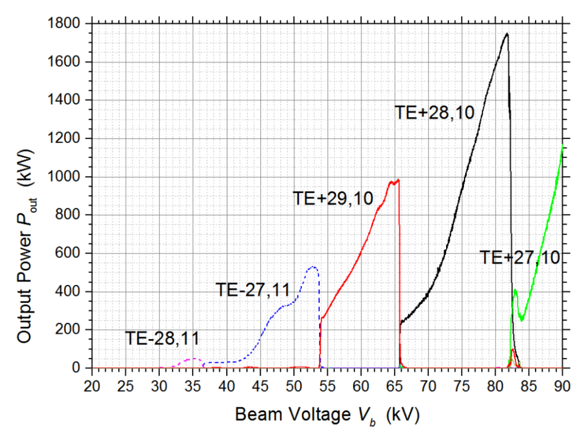

Fig. 1. Typical gyrotron multi-mode start-up (44 competing modes) at 55 A electron beam current, showing excitation of the operating $TE_{28,10}$ mode at the nominal beam energy (80 keV).

- The design of the CVD diamond window will be practically the same to that of the 1 MW gyrotron. However, in view of the higher power and the plan to use silicone oil cooling, a series of CFD conjugated heat transfer and structural analyses were carried out. The analyses validated the window performance, namely the resulting temperatures and stresses, which are well below the critical limits. For instance, even in the worst case scenario concerning the absorbed power in the disk, the resulting maximum temperature is 215°C, well below the conservative limit of 250°C assumed for CVD diamond.
- The collector design for the 1.5 MW CW prototype will be identical to that of the 1 MW W7-X gyrotrons. It is foreseen that the collector can handle the ~50 % increase in power of the spent electron beam. To further improve the homogeneity of the loading on the collector wall, sophisticated schemes for the magnetic axial electron beam sweeping [12] combined with transversal beam sweeping are foreseen.

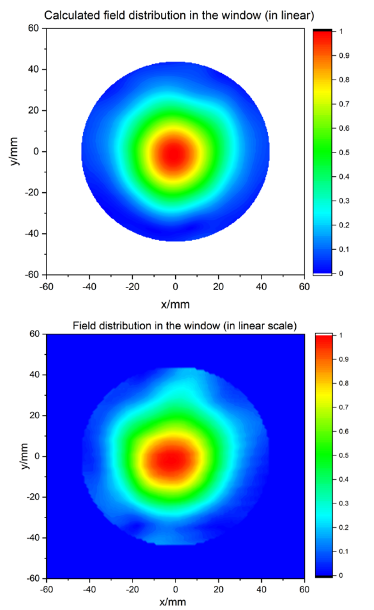

Fig. 2. Calculated (top) and measured (bottom) microwave beam profiles at the window plane.

The short-pulse gyrotron prototype was manufactured at KIT. This gyrotron will support the development of the CW prototype and mitigate the technical risks by providing experimental validation of the scientific design of all critical components. First experiments with the short-pulse tube are expected in September 2020. The corresponding industrial CW prototype is being manufactured at Thales Electron Devices SAS, with a foreseen tube delivery by mid-2021.

III. Current Status

The assembled short pulse prototype gyrotron has been installed in the KIT test-stand (see Fig. 3). Following vacuum and voltage stand-off checks, a first conditioning phase has been carried out. The filament heating current reached the nominal value.

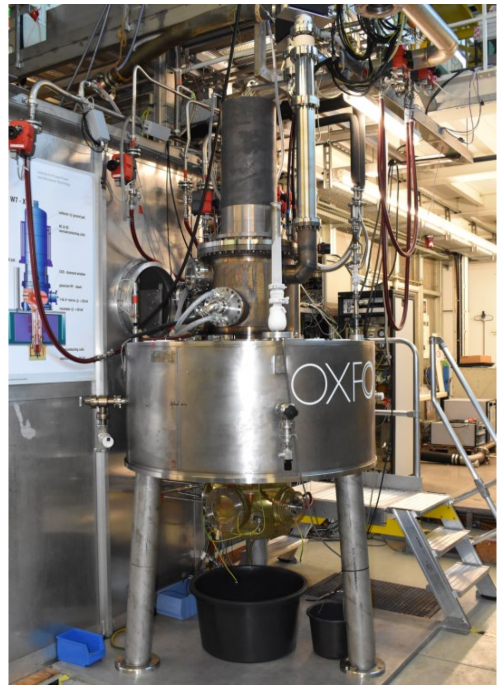

Fig. 3. Short-pulse prototype 140 GHz, 1.5 MW gyrotron installed in the KIT test-stand ready for first experiments.

Additional preparations to operate the CW prototype tube in the KIT test-stand are ongoing. This includes the adaption of a high-power microwave load (with a quasi-optical transmission line from the gyrotron), the various cooling circuits, calorimetry, and microwave frequency diagnostics. In addition, the existing old liquid Helium based superconducting magnet will be replaced by a new, cryogen-free system.

Acknowledgement

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research programme 2014-2018 and 2019-2020 under grant agreement No. 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission. Part of the simulations was performed on the EUROfusion High Performance Computer (Marconi-Fusion).

References

[1]. T. Klinger *et al*., *Nucl. Fusion* **59** 112004, 2019
[2]. R. C. Wolf *et al*., *Plasma Phys. Control. Fusion* **61** 014037, 2019
[3]. R. C. Wolf *et al., Phys. Plasmas* **26** 082504, 2019
[4] Yu. Turkin *et al*., in preparation
[5]. K. A. Avramidis *et al*., *EPJ Web of Conf.* **203** 04003, 2019
[6]. I. Gr. Pagonakis *et al.*, *Phys. Plasmas,* **23**, 083103, 2016.
[7]. I. Gr. Pagonakis *et al.*, *Phys. Plasmas*, **23**, 023105, 2016.
[8]. Jianbo Jin *et al.*, *IEEE Trans. Microw. Theory Techn.* **57** 1661, 2009.
[9]. I. G. Chelis *et al*., *IEEE Trans. Electron Devices* **65** 2301, 2018.
[10]. I. G. Chelis *et al*., *44th Int. Conf. Infrared, Millimeter and THzWaves*, 1 - 6 September 2019, Paris, France.
[11]. I. G. Chelis, EUROfusion WPS1 2019 deliverable S1-WP19-20.IH-T004-D003, https://idm.euro-fusion.org/?uid=2MZ5UE.
[12]. S. Illy et al., *43rd Int. Conf. Infrared, Millimeter and THz Waves*, 9 -14 Sep. 2018, Nagoya, Japan.