WPHCD-CPR(18) 19588

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Preprint of Paper to be submitted for publication in Proceeding of 27th IAEA Fusion Energy Conference

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

IOP Publishing Journal Title
Journal **XX** (XXXX) XXXXXX https://doi.org/XXXX/XXXX

Overview of recent gyrotron R&D towards DEMO within EUROfusion Work Package Heating and Current Drive

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Received xxxxxx
Accepted for publication xxxxxx
Published xxxxxx

Abstract

Gyrotron R&D within EUROfusion Work Package Heating and Current Drive is addressing the challenging requirements posed on gyrotrons by the European concept for a demonstration fusion power plant (EU DEMO). The R&D activities are organized in five main branches: these are the experimental verification of the advanced coaxial gyrotron technology at long pulses, the development of a coaxial gyrotron meeting the EU DEMO requirements, the development of multi-stage depressed collectors for enhanced energy recovery, the development of large broadband diamond windows to allow fast frequency tunability of the gyrotron, and the studies on further innovations and improvement of critical gyrotron components, in view of optimization of performance, reliability, and industrialization. The paper reports on the progress of these activities, on the recent results, and on near-term planning.

Keywords: DEMO, ECRH, gyrotron

1. Introduction

Within the Work Package Heating and Current Drive (WPHCD), coordinated by the Power Plant Physics and Technology Department of EUROfusion, extensive studies are ongoing, which cover three different systems for plasma heating and current drive. These are, namely, systems using electron cyclotron waves, ion cyclotron waves, and neutral beam injection [1]-[2]. The studies are in line with the European Fusion Roadmap towards a demonstration power plant (DEMO). Currently, the primary focus is on a pulsed (> 2 h) DEMO plant concept design (baseline EU DEMO1), in order to eliminate integration risks and resolve design interface issues [3]. Alternative configurations towards a more advanced future power plant are also under investigation [4].

The work breakdown structure of WPHCD, launched in 2014, includes branches dedicated to the conceptual design of the Electron Cyclotron (EC) wave system [5], as well to R&D focused mainly on the microwave source, the gyrotron [6]. Gyrotron R&D is a necessary step to bridge the gap between today's state-of-the-art gyrotrons and future gyrotrons for DEMO. This gap is clearly illustrated in Table I, where the main gyrotron requirements for ITER [7] and for EU DEMO1 are compared. The presented requirements for the gyrotron for EU DEMO1 have been deduced within WPHCD in order to be consistent with the 2015 baseline for the EU DEMO1 and the associated proposed concept for the EC-system [8]. In should be noted that the gyrotron requirements remain the same in the current 2017 baseline [9], after its physics upgrade in 2018 [10].

From Table I, it is evident that significant challenges are posed by the need for dual-frequency operation and/or frequency step-tunability reaching frequencies above 200 GHz, as well as by the requirements for considerably higher power, efficiency, and level of Reliability – Availability – Maintainability - Inspectability (RAMI). Gyrotron R&D within WPHCD is addressing those challenges by exploring innovative approaches along the lines detailed in Section 2. In addition, and in order to keep the R&D relevant with respect both to possible baseline changes and to alternative reactor configurations towards a future power plant, efficient MW-class gyrotron operation at higher frequencies (~240 GHz) is also investigated.

Table I. Gyrotron Requirements

	EU DEMO1 [8]	**ITER**
Center frequency	170/204 GHz	170 GHz
RF output power	2 MW	1 MW
Overall efficiency	≥ 60 %	50 %
Tunability range (in case of frequency-steering)	±10 GHz, in steps of 2-3 GHz	-
RAMI level	Demonstration power plant	Experimental reactor

This paper reports on the progress of gyrotron R&D within WPHCD, which is driven by all the aforementioned challenges. In Section 2, the recent results are presented, detailed with respect to the five main tasks around which the research is organized. These are the experimental verification of the advanced coaxial gyrotron technology at long pulses, the development of a coaxial gyrotron meeting the EU DEMO requirements, the development of multi-stage depressed collectors for enhanced energy recovery, the development of large broadband diamond windows to allow fast frequency tunability of the gyrotron, and the studies on further innovations and improvement of critical gyrotron components, in view of optimization of performance, reliability, and industrialization. Section 3 describes the key infrastructure supporting the R&D, and Section 4 summarizes the results and gives an outlook for the activities.

2. Progress of gyrotron R&D activities

2.1 Coaxial gyrotron technology at longer pulses

The advanced concept of the coaxial-cavity gyrotron has been selected as being the more promising, compared to a hollow-cavity gyrotron, towards the higher power and higher frequency targets. The enhanced mode selectivity of coaxial cavities permits stable operation at very high-order operating modes, which allows the use of larger cavity dimensions. Hence, the cavity can better withstand the higher Ohmic losses instigated by the increased power and the higher operating frequency.

The modular 170 GHz, 2 MW short-pulse coaxial gyrotron at Karlsruhe Institute of Technology (KIT) has already exhibited excellent performance in pulses of several ms [11]. The next step for the coaxial gyrotron technology towards DEMO is to prove experimentally its capability for long-pulse operation, especially with respect to the cooling and alignment of the coaxial insert. To this end, the 170 GHz, 2 MW short-pulse coaxial gyrotron at KIT has been upgraded with new, water-cooled components [12-13]. In particular, the beam tunnel, the cavity, the quasi-optical system, and the mirror box have now independent cooling systems. A very important aspect of this upgrade is that the modularity has been preserved, i.e. an easy implementation and testing of new improved subcomponents is possible.

The first target of the upgraded gyrotron is to extend the pulse length up to 100 ms, provided that a simple axial beam-sweeping system is used for the collector. It is expected that, at this pulse length and using the independent cooling systems, a reliable assessment of the expected thermal loading of the various gyrotron components (and especially of the coaxial insert) in Continuous-Wave (CW) operation will be possible.

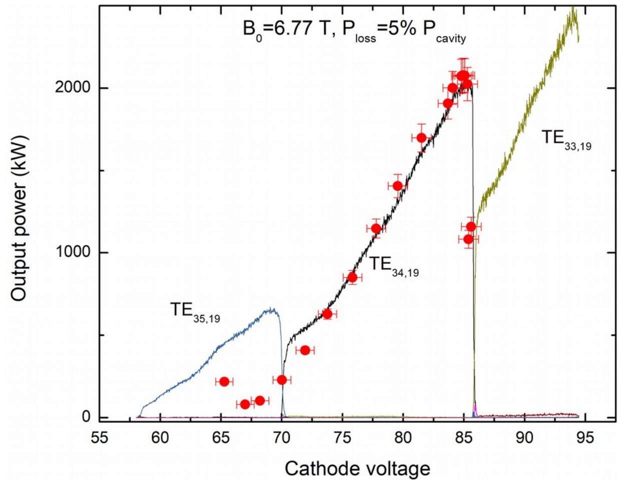

Figure 2. Output power at the gyrotron window versus the acceleration voltage as simulated (solid lines) and measured (red points) for the coaxial gyrotron configuration of Fig. 1, tested at KIT. The beam current reaches 81 A at 85 kV.

In order to first validate the design and construction of the new water-cooled components, a gyrotron assembly using the new components and the old diode electron gun of the short-pulse gyrotron was tested in short pulses (a few ms) with the goal to reproduce the previous behavior of the short-pulse tube [14]. This configuration is shown in Fig. 1. The validation was fully successful, since, at nominal parameters, the operating $TE_{34,19}$ mode was stably excited at 169.9 GHz with an output RF power close to 2.1 MW and an overall efficiency slightly above 30 % in non-depressed collector operation. After further parameter optimization, the RF power was increased to 2.2 MW with ~33 % overall efficiency.

The experimental results are in very good agreement with the simulations [15]. A comparison is shown in Fig. 2. For the calculation of the magnetic field profile and the electron beam parameters at each experimental pulse, the code *Ariadne* [16] was used, taking as input the currents applied to the coils of the super-conducting magnet as well as the applied acceleration voltage and the measured electron beam current. Then, the calculated magnetic field profile and electron beam parameters were used as input to the code EURIDICE [17], to simulate the beam-wave interaction in the gyrotron cavity & uptaper (considering 61 competing modes) and calculate the RF power at the end of the uptaper. To compare with the measured value of the RF power at the gyrotron window, a typical 5 % power loss between the end of the uptaper and the window was assumed. In order to achieve the best agreement between experiment and simulation, an adjustment of 0.15 % in the value of the magnetic field B_0 used in the simulation was adopted. Given that the uncertainty in the values of the currents applied to the magnet coils is of the order of 0.1 %, and considering the possibility of a small movement of the coils at high field, the adopted adjustment is justified as it lies within the uncertainty range. The reason for the remaining discrepancy between experiment and simulation at low voltages below 70 kV is under investigation. Most probably, the beam quality at such low voltage is worse than expected, which leads to an earlier suppression of the $TE_{35,19}$ mode.

Figure 1. The 170 GHz, 2 MW coaxial-cavity gyrotron configuration at KIT with the new water-cooled components and the old short-pulse diode gun before (left) and after (right) installation in the magnet. [14]

A key point for the verification of the coaxial gyrotron concept at long-pulse operation is the behavior of the coaxial insert, in terms of cooling and alignment. For this reason, in parallel to the experimental investigations, multi-physics numerical simulations focused on the performance of the cooling system of the insert [18]. It was found that the existing water cooling can easily support even CW operation, by providing large margins both with respect to the Ohmic loading of the insert and to a possible insert misalignment. In particular, the expected maximum Ohmic loading at nominal 2 MW operation is 0.12 kW/cm^2 and the insert can be aligned with an accuracy better than 0.1 mm. According to the simulation, the maximum acceptable values for the Ohmic loading and the misalignment of the insert are 0.39 kW/cm^2 and 0.2 mm, respectively.

Multi-physics numerical investigations on the cooling of the cavity wall, taking into account the existing water-jacket cooling, were also performed in collaboration with Politecnico di Torino [19]. They showed that the existing simple cooling concept can support operation up to 150 ms before the temperature of the cavity wall reaches 250ºC, which is considered to be the safety limit. This makes the existing cooling circuit consistent with the first goal of increasing the pulse-length up to 100 ms. For longer pulses, more advanced cooling configurations, like those already used in high-power CW gyrotrons, need to be considered and pertinent investigations are ongoing.

2.2 Design of a 2 MW 170/204 GHz coaxial gyrotron

To keep the development path towards the DEMO gyrotron as fast and cost-effective as possible, the design of a 2 MW, 170/204 GHz coaxial gyrotron has been initiated using the existing 170 GHz coaxial gyrotron at KIT as starting point [20-21]. The simulation results show that a good performance can already be achieved with only minor modifications of the existing modular gyrotron. The first necessary modification is the change of the axial position of the coaxial electron gun, in order to operate in the magnetic field profile of the newly procured 10.5 T superconducting magnet (see Section 3). Taking this into account, multi-mode beam-wave interaction simulations using EURIDICE with electron beam parameters obtained by *Ariadne* have been performed. The simulations have been as realistic as possible at this stage, considering the expected spreads in electron beam parameters, the axial variation of the magnetic field profile, and the Ohmic losses. It was shown that, even with the existing coaxial cavity, MW-class performance can be achieved both at 170 and at 204 GHz. A more balanced performance with respect to the two frequencies can be reached, if the cavity is modified to have a 2.4 mm shorter midsection. Table II summarizes the simulated performance of the cavity for the dual-frequency gyrotron.

A new mirror-line quasi-optical mode converter has also been designed, in order to optimize the conversion of the cavity mode to Gaussian mode at both frequencies. The calculated Gaussian mode content at the launcher aperture is 97.2 % at 170 GHz and 96.6 % at 204 GHz.

Finally, interaction simulations showed that MW-class operation at 237 GHz seems also possible with the $TE_{48,26}$ mode, delivering 1.6 MW of RF power in the cavity at 30 % interaction efficiency. Frequencies around 240 GHz can be attractive for advanced future power plants [4] and this has always been considered within WPHCD, keeping the gyrotron R&D relevant also to that frequency range [22-23].

2.3 Investigations on multi-stage depressed collector concepts

The target of ≥ 60 % efficiency for the DEMO gyrotron motivates the development of advanced Multi-Stage

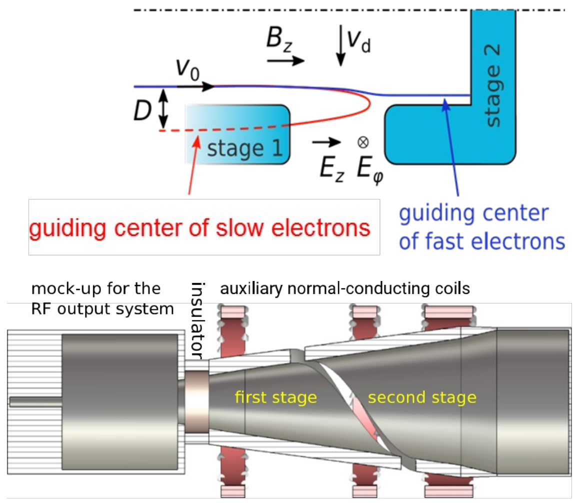

Figure 3. Schematic of the underlying concept for an MDC based on **E**×**B** drift (top) and of a two-stage MDC with helical electrodes (bottom) [27]. The helical cut of the MDC separates the two stages and also produces the azimuthal electric field $\mathbf{E}_\varphi$, necessary for the radial drift of the electron guiding center with velocity $\mathbf{v}_d = (\mathbf{E}_\varphi\times\mathbf{B}_z)/B_z^2$.

Depressed Collectors (MDC) to increase the energy recovery from the spent electron beam. Given that in the gyrotron the electron beam is guided by a strong magnetic field to the collector, the required separation of electrons according to their energy, necessary for MDC operation, is challenging. Extensive investigations on different MDC concepts [24-25] led to a very promising configuration, based on the **E**×**B** drift concept, which was first proposed for gyrotrons in [26]. This configuration adopts helical electrodes for the realization of the concept [27]. Schematics of the **E**×**B** drift concept and of a two-stage MDC with helical electrodes are plotted in Fig. 3.

The unique advantages of the suggested MDC include very good handling of secondary electrons and high robustness against stray magnetic fields and electron beam misalignments. The collector configuration has been further optimized in terms of length and minimization of reflected current, using commercial 3-D numerical tools for more accurate simulations [28]. With an optimized two-stage design, a collector efficiency of 77 % has been numerically demonstrated. Assuming 35 % interaction efficiency and 10 % internal gyrotron losses, this corresponds to 63 % overall gyrotron efficiency. The efficiency could be further increased by increasing the number of collector stages. The engineering design of a prototype short-pulse two-stage **E**×**B** MDC has been initiated, in view of a future proof-of-principle experiment.

2.4 Development of large broadband diamond windows

To allow fast frequency step-tunability at ~2 MW gyrotron power (in order to support plasma instability control by fine-tuning the energy deposition location with the frequency), the elegant and compact solution of a Brewster-angle, Chemical Vapor Deposition (CVD) diamond window is pursued. As the efficient cooling of the elliptical window can be challenging, several solutions have already been investigated within WPHCD [29]. The major challenge, however, is to produce a 180 mm diameter diamond disk of ~2 mm thickness with low intrinsic stresses, and to develop the joining technique in the Brewster angle (67.2° for diamond) for a window unit with 63.5 mm aperture and 2 MW transmission (Fig. 4). Given that today's industrial plasma reactors are able to deposit optical grade CVD diamond on substrates of 120-150 mm diameter only, new diamond window technologies are investigated to increase the diameter up to 180 mm, as this is a new field for the diamond manufacturers.

Very promising growth test experiments for 180 mm disks have been initiated at the site of the industrial partner Diamond Materials (Diamond Materials GmbH, Hans-Bunte-Str. 19, 79108 Freiburg, Germany, http://www.diamond-materials.com) [30]. Two experiments ran for 400 and 350 hours, with a lower and a higher growth rate, respectively, producing the first, worldwide, 180 mm diamond wafers with a thickness of 0.30 to 0.45 mm. The wafers are quite homogeneous and of good optical quality, as assessed by eye-check. A picture is shown in Fig. 4. Due to the very small thickness, the two wafers did not remain in one piece after dissolving the silicon substrate. Nevertheless, it was possible to cut a 39 mm diameter disk to be used for loss-tangent measurements at KIT. These measurements are ongoing.

Table II. Operating parameters and calculated performance of a 2 MW, 170/204 GHz coaxial gyrotron design

Mode	$TE_{34,19}$		$TE_{40,23}$	
Cavity	Existing	New	Existing	New
Frequency (GHz)	170.00	170.04	204.14	204.17
Beam voltage (kV)	90.0	90.6	79.2	86.5
Beam current (A)	75	75	70	75
Magnetic field (T)	6.86	6.88	8.15	8.23
Electron velocity ratio	1.3	1.3	1.2	1.2
RF power at cavity (MW)	2.3	2.5	1.7	2.1
Interaction efficiency (%)	34.5	37.0	31.0	32.3

2.5 Advances on performance and reliability of gyrotron components

The required high RAMI level of a DEMO gyrotron calls for further optimization of all critical components. In addition, improvements with respect to robustness against manufacturing tolerances are necessary for the next step of industrialization of fusion gyrotrons.

2.5.1 Electron gun. An advanced triode-type coaxial electron gun has been designed at KIT and procured by the industrial partner Thales Electron Devices (TED, Vélizy-Villacoublay, France, www.thalesgroup.com) [31]. The gun is shown in Fig. 5. Following the experimental campaign discussed in Section 2.1, the old short-pulse diode gun was removed from the gyrotron and was replaced with the new triode gun. This gun is designed to be free of electron trapping mechanisms, i.e. compatible with long-pulse operation [32], and thus the increase of the pulse length up to 100 ms can be pursued with the present coaxial gyrotron configuration. An innovative feature of the new gun is that the emitter edges are coated with anti-emissive material, in order to minimize the influence of manufacturing tolerances and edge effects on the electron beam quality [33]. A mock-up of the emitter is also shown in Fig. 5. This is the first time this technology is used for a gyrotron emitter in the EU and it is expected to result in increased reproducibility and reliability of electron guns for gyrotrons. Additional collaboration with TED with respect to gun technology has also been established within WPHCD, with the aim to investigate technological improvements related to the alignment and temperature homogeneity of the emitter.

2.5.2 Beam tunnel. The way to secure robust and reliable gyrotron performance is to expand, as much as possible, the operating parameter range of stable, high-power oscillation of the working mode. A critical component in that respect is the gyrotron beam tunnel, whose function is to suppress any possible parasitic oscillations in the region of the magnetic compression of the electron beam, i.e. between the gun and the cavity.

Today's European beam tunnel technology is adopting the stacked beam-tunnel concept with alternating indented rings of copper and rings of absorbing ceramic [34]. Such beam tunnels have supported successful operation of the European gyrotrons for W7-X and ITER over specific parameter areas. However, given that DEMO gyrotrons require more energetic electron beams (higher currents) and in order to enlarge the parameter area of stable operation, advances in the beam tunnel design are under intensive investigation within WPHCD, as the onset of parasitic oscillations limits

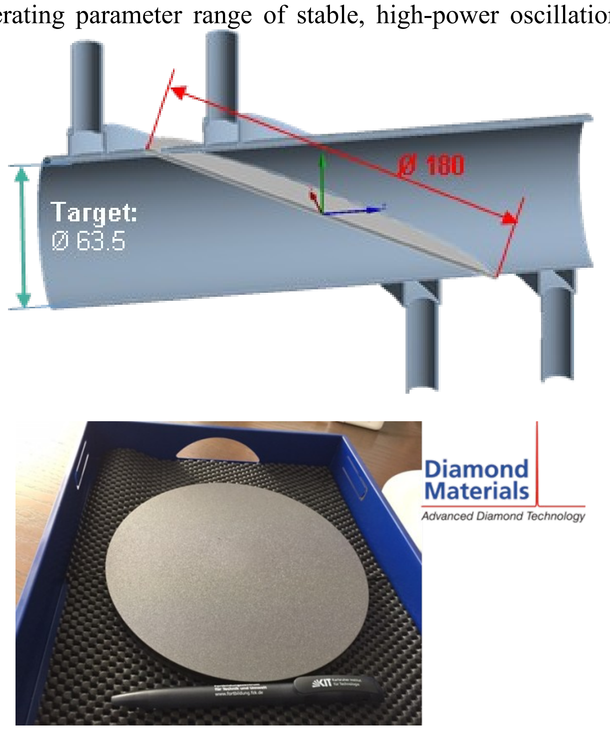

Figure 4. Schematic of the envisaged diamond window brazed in the waveguide at the Brewster angle (top) and picture of the first produced, worldwide, CVD diamond wafer of 180 mm diameter and of 0.3 to 0.45 mm thickness on the substrate (bottom).

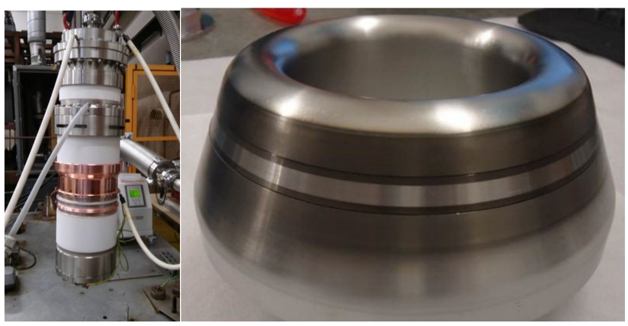

Figure 5. The new triode coaxial electron gun for the 170 GHz, 2 MW longer-pulse coaxial-cavity gyrotron at KIT (left), and a mock-up of its cathode nose and the emitter ring with coated edges (right).

the stability range of the operating mode. The challenge lies primarily on the accurate modelling of the complicated and highly overmoded structure of the beam tunnel. To address this, semi-analytical as well as purely numerical modelling tools have been under development. In particular, the code NESTOR [35], based on a semi-analytical model for the stacked beam tunnel to calculate the resonant modes in the absence of an electron beam, is now being upgraded in order to also address self-consistently the beam-wave interaction using a gyro-averaged model for the particle motion [36-37]. The merit of the upgraded NESTOR is that it will be able for fast calculations, taking advantage of the semi-analytical method and gyro-averaging. However, the underlying model cannot address two additional features of the stacked beam tunnel concept; namely, the tapered geometry and the indentations on the copper rings. For this reason, the development of COCHLEA, which is a new 3D full-wave code based on FDTD and Particle-In-Cell (PIC) methods and focusing on cylindrical geometries, has been initiated in 2016 at the National and Kapodistrian University of Athens. The electromagnetic module of the code is currently being benchmarked by calculation of dispersion characteristics of finite-length periodically corrugated waveguides [38]. The PIC module is still under development.

Alternative beam tunnel concepts, like a fully ceramic or a fully metallic beam tunnel, are also promising and have been in use outside the EU since a long time, e.g. [39-40]. Studies on a fully ceramic beam tunnel are ongoing within WPHCD, since such a beam tunnel would also have the advantage of simpler construction. The self-consistent linear and spectral code TWANGlinspec at the Swiss Plasma Center has been upgraded to address tapered magnetic fields [41] and smooth boundaries with lossy dielectric. Preliminary calculations show significant increase in the starting current of resonant parasitic modes, if a metallic smooth-wall beam duct is coated with BeOSiC or SiC. In parallel to those investigations, the possibility of localized parasitic oscillations, emerging by gyro-backward-wave interaction in the metallic spacer used to connect the beam tunnel to the gyrotron cavity, has been identified [42]. Following this finding, studies on possible guidelines for the spacer design have been initiated. The possibility to use a fully metallic beam tunnel but with specially designed surface, as this would be the simplest and cheapest option, is also under investigation.

2.5.3 Cavity. From the gyrotron cavity side, the enlargement of the parameter space of stable operation is related to the mode selectivity. A way to further increase the already advanced mode selectivity of coaxial cavities is to add mode-converting corrugations on the outer wall [43]. Studies on such cavities have already been done within WPHCD [44] using the code CCCI [45], which provides full-

Figure 6. Key components of FULGOR test stand at KIT. Top: high-voltage cage with the modular main power supply. Bottom, left: demineralized water cooling plant. Bottom, right: 5 MW cooling tower on rooftop (currently one, later two towers).

wave modelling of these cavities in the absence of the electron beam. To include the electron beam in the investigations, an interface has been recently developed [37] between CCCI and EURIDICE, which makes beam-wave interaction simulations in such cavities possible. Following this, investigations on the possibility to improve the cavity of the 170 GHz coaxial gyrotron at KIT by adding corrugations on the outer wall have been initiated.

3. Large-scale infrastructure at KIT

The new Fusion Long Pulse Gyrotron Laboratory (FULGOR) at KIT is a test stand capable of 10 MW DC CW operation [46]. Although FULGOR is being built outside WPHCD, its contribution to the gyrotron R&D will be indispensable. Key components are shown in Fig. 6. The capabilities of the main high-voltage DC power supply, delivered in late 2017 by Ampegon AG (Turgi, Switzerland, www.ampegon.com) and accepted in 2018, are up to 90 kV / 120 A for 3600 s / 50 % duty cycle, and 130 kV / 120 A in short pulse (5 ms / 0.25 % duty cycle). There is also the possibility for up to 10 intermediate voltage taps for multi-stage depressed collector operation, freely selectable in 1.2 kV steps. A 50 kV / 100 mA CW Body Power Supply is also on order to Ampegon AG.

With support from WPHCD, the purchase specification for a 10.5 T super-conducting magnet for FULGOR with a bore hole of 261 mm has been prepared. The magnet will be cryogen-free with two cooling heads and no He-reservoir. It will be also equipped with a 3×4-coil dipole coil system, to provide the means for accurate alignment of the coaxial insert in coaxial gyrotrons. The magnet has been ordered to Tesla Engineering Ltd. (Storrington, UK, www.tesla.co.uk) and is expected to be delivered by middle of 2019. A schematic of the magnet is shown in Fig. 7. With the addition of this magnet, FULGOR will be able to support multi-MW DEMO gyrotron development up to 240 GHz.

4. Summary and outlook

Gyrotron R&D within EUROfusion WPHCD is progressing towards the development of an advanced, coaxial-cavity gyrotron for DEMO, satisfying all the challenging requirements deduced from the EU DEMO1 baseline. Regarding the verification of the coaxial gyrotron technology in long-pulse operation, the new water-cooled subcomponents for a longer-pulse 170 GHz, 2 MW coaxial gyrotron at KIT have been experimentally validated in ms pulses, as far as the scientific design and manufacturing are concerned. The experimental results are in a very good agreement with the simulations, verifying the available numerical tools. A new triode-type coaxial gun has been procured incorporating the technology of emitter with coated edges, which is new for gyrotron development in EU. The current modular coaxial gyrotron configuration at KIT, which includes the new gun and the water-cooled subcomponents, is ready for testing with the aim of increasing the pulse length up to 100 ms. The target of 1 s pulse is planned to be pursued as a second step. This should involve further upgrades of the modular coaxial gyrotron, including a CVD diamond output window, a long-pulse collector, and advanced cavity cooling.

Designs for the cavity and quasi-optical launcher of a 2 MW, 170/204 GHz coaxial gyrotron for DEMO, using the existing coaxial gyrotron at KIT as a starting point, have been obtained and validated by realistic simulations. The design studies will continue with the goal to produce an engineering design for a modular short-pulse prototype.

An optimized design of a two-stage depressed collector, based on the **E**×**B** concept, has also been achieved and the engineering design of a short-pulse prototype collector has been initiated, in view of a future proof-of-principle experiment.

The first, worldwide, 180 mm diameter wafer of CVD diamond with a thickness of 0.30 to 0.45 mm has been produced. This is a very important step towards a broadband Brewster-angle CVD diamond window, compatible with a 63.5 mm waveguide. More diamond growth experiments for 180 mm diameter disks are currently running, aiming at the required ~2 mm thickness.

The modelling of different beam tunnel concepts and of complex cavities with mode-converting corrugations has been advancing by further developing and/or upgrading in-house codes; namely, NESTOR, COCHLEA, CCCI, TWANGlinspec, and EURIDICE. The goal is to realize numerical tools able to model those components with the accuracy required to obtain improved and more reliable designs.

Finally, the construction of the key infrastructure for the development of the EU DEMO gyrotron, i.e. the new gyrotron test-stand FULGOR at KIT equipped with a new 10.5 T super-conducting magnet, is moving ahead. Test-stand and magnet are expected to be operational in 2019.

Acknowledgements

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training 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).

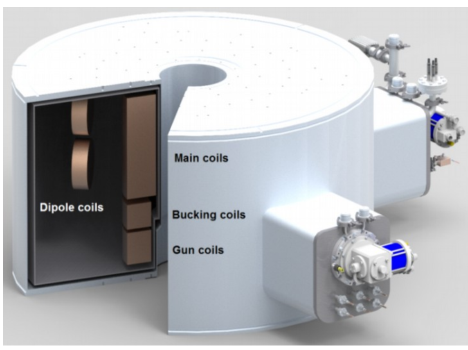

Figure 7. Schematic of the cryogen-free 10.5 T superconducting magnet ordered to Tesla Engineering Ltd.

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