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Design considerations for future DEMO gyrotrons: A review on related gyrotron activities within EUROfusion

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HIGHLIGHTS

- The research work on multi-megawatt fusion gyrotrons with an operating frequency significantly above 200 GHz together with an RF output power of more than 1 MW and a total gyrotron efficiency of better than 60% is summarized. It includes research on frequency tunable gyrotrons and multi-purpose gyrotrons.
- Principle feasibility of coaxial-cavity gyrotron technology is compared to conventional hollow-cavity technology. Both options are studied with regards to maximum achievable output power versus efficiency, operation stability and tolerances.
- Research for multi-stage depressed collectors (MSDC) is summarized.

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ABSTRACT

Long-term options for a steady-state DEMOnstration power plant may require the availability of gyrotrons with an operating frequency significantly above 200 GHz together with an RF output power of more than 1 MW and a total gyrotron efficiency of better than 60%. Frequency tuning in steps of around 2–3 GHz might be needed for control of plasma stability. Multi-purpose operation at frequencies with leaps of about 30 GHz might be considered for plasma start-up, heating and current drive at different operation scenarios. The combination of those requirements clearly challenges present-day technological limits. The R&D work within the EUROfusion WP HCD EC Gyrotron R&D and Advanced Developments is focusing on named targets. In particular, a centre frequency of around 240 GHz is under investigation. The coaxial-cavity gyrotron technology, and, as a possible fallback solution, the conventional hollow-cavity are under investigation. Both options are studied with regards to maximum achievable output power versus efficiency, operation stability and tolerances. Concerning the coaxial-cavity technology, an additional experimental investigation shall verify the predicted operation capabilities. Various promising concepts for multi-stage depressed collectors (MSDC) are under investigation. The research and development are completed by advancing the simulation and test tools capabilities significantly.

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1. Introduction

The European Fusion Roadmap [1] is focusing on the realization of a DEMOnstration power plant, which will produce substantial electrical power. Within the Power Plant Physics and Technology (PPPT) program, launched in 2014, the EUROfusion Consortium is conducting detailed studies of that possible future DEMO, which, besides producing electricity, shall be self-sufficient in tritium production while meeting the strict requirements on safety and environmental issues. The baseline (main technical requirements) for the design of the future DEMOnstration power plant is not finally decided yet. It follows that the ECRH requirements and the related technical solution might change in future. Nevertheless, presently, two variants are under consideration: a long-pulse version (Baseline: EU-DEMO1-2015), and a second variant (EU-DEMO2) operating in steady state, incorporating a larger current drive power and a larger bootstrap fraction. As part of PPPT, the research and development on Heating and Current Drive (HCD) covers three major heating methods, namely, the Electron Cyclotron Heating (ECH), the Ion Cyclotron Heating (ICH) and the Neutral Beam Injection (NBI). Target is to gather the technical data that, in conjunction with the physics requirements, will allow the selection of a proper heating mix for the future DEMOnstration power plant.

Within the present HCD work package (WP HCD) of the PPPT project, the ECH conceptual design focuses on the EU DEMO1-2015 baseline for a pulsed machine (>2 h) with an aspect ratio of 3.1 and a toroidal magnetic field $B_T = 5.7$ T, in which Electron Cyclotron Current Drive (ECCD) does not play a major role for pulse sustainment, but only is crucial for Neoclassical Tearing Mode (NTM) control during plasma flat top [2,3]. Based on the EU DEMO1-2015 baseline, two reference frequencies have been selected for conceptual designs of the DEMO ECH system: first, 170 GHz for heating, which ensures basic compatibility to the ITER ECH system [4], and second, 204 GHz for ECCD, taking into account a moderate upshift factor of 1.2 between the frequency for the heating function and the one for current drive. As stated, the baseline of EU-DEMO1 is not yet finally decided, thus the scenario modelling is still ongoing in the program and the final choice will be made once the DEMO design phase is completed. While the EC conceptual design follows the EU-DEMO1-2015 baseline for a pulsed machine, gyrotron R&D and Advanced Developments is focused on a possible ECCD operation at much higher frequency around 240 GHz, originally considered as a compromise between the optimum ECCD frequency for the EU-DEMO1-2012 baseline developed from [5] and a reasonable operating frequency for megawatt-class gyrotrons, located sufficiently above 200 GHz. This compromise facilitates the selection of ECH and ECCD frequencies for a future Fusion Power Plant (FPP) appropriately, as presented in [6]. There, a coherent strategy to develop a stepladder ITER-DEMO-FPP has been presented. It assumes that the plasma scenario is similar in all three devices to ensure a credible extrapolation from device to device. Following [6] the toroidal magnetic field B_T of a future FPP would be located at 6.1 T or even higher. Considering an upshift factor of 1.4 for CD, again, this would lead to a current drive frequency of around 240 GHz. It is a simple estimate for central CD using an optimum toroidal angle. It is not considering the various possible scenarios for CD and limiting factors, such as CD for NTM stabilization located at the periphery. Finally, selection of the operating frequency in the project is in line with the advanced scenario of the Chinese Fusion Engineering Test Reactor (CFETR) at phase II for which a similar CD frequency of 230 GHz is currently considered [7].

Additionally to the operation at significantly above 200 GHz, *multi-purpose (multi-frequency) operability* and *frequency step-tunability* of gyrotrons are under investigation. Multi-purpose gyrotrons produce RF output at frequencies corresponding to multiples of the half-wavelength of their single-disc RF diamond window (e.g. ~34 GHz steps for a window thickness of ~1.85 mm), one at each time, allowing EC heating at various magnetic field configurations (slowly-varying) or at different frequencies for heating and current drive (e.g. 136/170/204/238 GHz). Multi-purpose gyrotrons have already been developed or are under consideration for lower frequencies, e.g. for ASDEX upgrade at IPP Garching [8], TCV at EPFL, Lausanne [9] and JT-60SA at Japan [10]. Frequency step-tunability, on the other hand, means switching of the operating frequency within seconds and in steps of 2–3 GHz, allowing fine-tuning of the deposition location. In [11,12], the principle operation of a megawatt-class D-band (111.6–165.7 GHz) gyrotron has been shown for short-pulse operation (ms). This gyrotron uses a broadband CVD Diamond-disc elliptic window placed at the Brewster angle of $\theta_{Br} = 67.2^\circ$ with a major axis of 140 mm corresponding to a waveguide diameter of 50 mm. Most important in the realization of Chemical Vapour Deposition (CVD) diamond-disc Brewster-angle windows for continuous wave (CW) gyrotrons is, first, to find a proper solution for the production of sufficiently large diamond-disc windows, second, to realize suitable assembly technologies for merging the diamond-disc window with the copper cuff, and, third, to achieve sufficient cooling during operation.

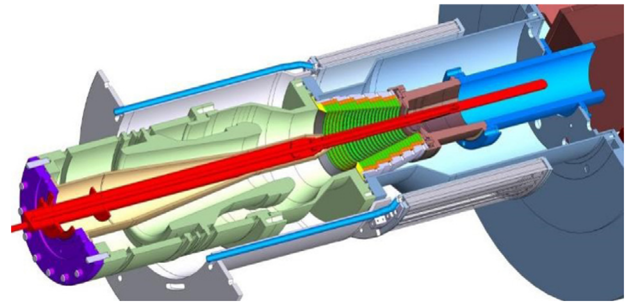

Fig. 1. 3D image of a typical coaxial insert (red) within a coaxial-cavity gyrotron. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Finally, the advanced development in the WP HCD project of the PPPT program focuses on pushing the total efficiency of gyrotrons to above 60% by using multi-stage depressed collectors (MSDC), analogous to those used in travelling-wave tubes and klystrons [13]. Even though previous work on MSDCs for gyrotrons exists [14–16], to the best knowledge of the authors, none of these concepts have been experimentally validated yet. Two physical concepts for MSDCs are under investigation.

2. R&D and AD for Future Fusion Gyrotons

2.1. Conceptual designs for 240 GHz gyrotrons

Two main design paths are known for high-power fusion gyrotrons: the conventional hollow-cavity design and the coaxial-cavity design [17]. Both concepts are under investigation to check the feasibility of megawatt-class CW gyrotrons operating at around 240 GHz. Hollow-cavity designs have been used for the 1 MW gyrotrons for Wendelstein 7-X (W7-X) [18] and ITER [19]. The coaxial-cavity concept has been used lately in Europe as a possible 2 MW option for ITER [20]. Fig. 1 shows the 3D view of a coaxial-cavity gyrotron.

For both concepts, theoretical studies are focusing on the maximum achievable RF output power and efficiency versus operating stability, manufacturability and robustness. At the begin of this research, it is assumed, that the coaxial-cavity design will offer the higher maximum achievable output power due to better mode separation and lower voltage depression. On the other hand it is