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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 $\theta_{\mathrm{Br}} = 67.2^\circ$ 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.

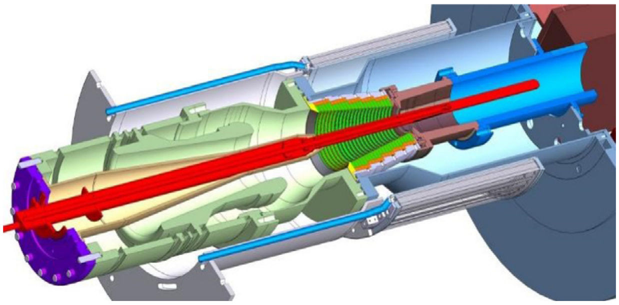

Fig. 1. 3D image of a typical coaxial insert (red) within a coaxial-cavity gyrotron. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

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

Table 1
Design targets and constraints.

Parameter	Value
Frequency	230–240 GHz
RF output power	1/2 MW
Total gyrotron (“plug-in”) efficiency	>60%
Beam-wave interaction efficiency	>35%
Gaussian mode content	≥98%
Fast frequency-tunability step	2–3 GHz
Multi-frequency step	30–40 GHz
Constraint	Value
Peak Ohmic wall loading at cavity	≤2 kW/cm^2
Peak Ohmic loading on coaxial insert	≤0.2 kW/cm^2
Emitter current density	≤4 A/cm^2
Electric field at cathode	≤7 kV/mm
Width of electron beam in cavity	≲λ/5
Emitter radius	∼50–70 mm

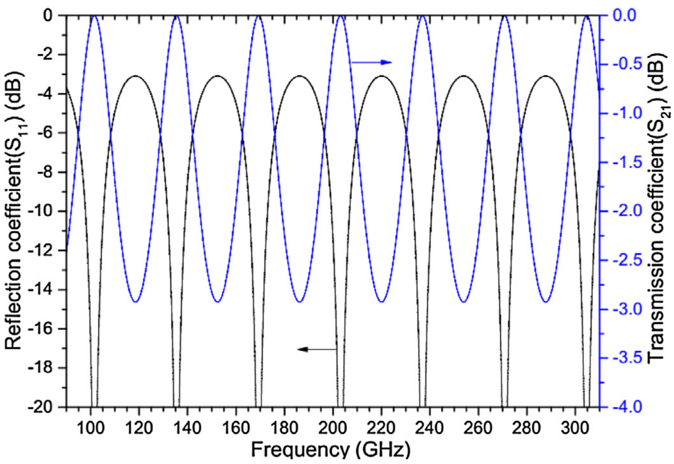

Fig. 2. Calculated reflection coefficient (S_{11}) and transmission coefficient (S_{21}) of a single-disc CVD-diamond RF output window ($\varepsilon_r = 5.67$, $d = 1.861$ mm).

Table 2
Calculated output power and efficiency for the three-frequency coaxial-cavity gyrotron.

Window thickness ($N \cdot \lambda/2$)	5	6	7
f (GHz)	170	203.75	237.5
$\chi_{m,p}$	113.1	135.6	158.1
Magnetic field B (T)	6.82	8.22	9.58
Output power P (MW)	1.8	1.9	1.9
Efficiency (%)	31	32	33

including a significant larger complexitiy in the construction due to the additional inner conductor. It is exactly the target of the studies to finally identify the individual limits of both concepts. It shall enable to do a final decision for one of the both concepts. So far, the focus has been on the maximum achievable output power under given physical constraints. Both designs shall meet the basic physical constraints and technical restrictions given in Table 1 [21]. In general, the RF output power of a high-power gyrotron operating at a mode $TE_{m,p}$ is limited by the maximum allowed thermal loading of the cavity wall. For hollow-cavity gyrotrons and, as a good approximation, for coaxial-cavity gyrotrons it scales with $f^{5/2}/[\chi_{m,p}{}^2 \cdot (1-(r_{\text{caustic}}/r_{\text{cavity}})^2)]$ as mentioned in [22]. In this equation f is the operating frequency of the gyrotron, and $\chi_{m,p}$ is the eigenvalue of the operating mode $TE_{m,p}$, where m and p are the azimuthal and radial index of the mode, respectively (for hollow cavities, $\chi_{m,p}$ is also the pth-root of the derivative of the Bessel function $J_m(\chi)$). $r_{\text{caustic}}/r_{\text{cavity}} = m/\chi_{m,p}$ is the relative caustic radius of the mode. Due to this, operation at megawatt power levels and significantly above 200 GHz is only possible if the operating mode has a very high eigenvalue. Since the operating mode of a gyrotron is a transversal electric (TE) mode close to cutoff, the cavity radius r_{cavity} can be estimated using the relation $r_{\text{cavity}} \approx c \cdot \chi_{m,p}/(2 \cdot \pi \cdot f)$, where c is the speed of light. As stated in [21], the corresponding eigenvalue of the selected mode should be, in any case, larger than $\chi_{m,p} = 95$ to fulfil the requirements shown in Table 1. As the mode eigenvalue increases, the mode spectrum becomes dense. In the case of very high-order modes, it becomes increasingly difficult to excite the desired operating mode during start-up due to the competing modes.

For multi-frequency designs, high-order operating modes are advantageous, as it can be shown that coupling spectra of such modes [23] are nearly identical for nearby modes. Therefore, the mode series for a multi-frequency gyrotron can be selected according to different criteria than only by evaluating the coupling spectra of the individual modes. In [24], a mode selection strategy for highly overmoded multi-frequency gyrotrons with a quasi-optical output coupler and a single-disc window is derived: The selected operating frequencies of the desired modes shall correspond to the reflection minima of a single disk window, according to the relation $f_N = c/(2 \cdot d \cdot \varepsilon_r{}^{0.5} \cdot N) = f_B \cdot N$, where d is the width of the window and N is an integer value which describes the thickness of the window in relation to the wavelength. The minimum and maximum widths for windows are given by mechanical stability and acceptable cost: The typical width of CVD-diamond windows ($\varepsilon_r = 5.67$) is between 1.50 mm and 2.25 mm, which corresponds to fundamental frequencies f_B between 42 GHz and 28 GHz. In the current analyses the width of the RF window is always considered to be 1.861 mm which is basically the same width as used for the ITER gyrotrons. The scattering parameters of this kind of window are shown in Fig. 2.

The described strategy leads to a rating scheme for series of operating modes; the main operating mode can then be chosen from a multi-frequency-suitable series. Based on these considerations, one finds that a coaxial-cavity gyrotron operating at three different frequencies with the $TE_{49,29}$-mode at 237.5 GHz is expected to retain sufficiently low internal losses if operated at the allied modes $TE_{42,25}$ at 203.6 GHz and $TE_{35,31}$ at 170 GHz. From the simulation an output power of about 1.9 MW seems to be possible even if a very conservative value for the conductivity of $\sigma = 1.4 \cdot 10^7$ S/m is taken into account. The calculated interaction efficiency is about 33%. In the simulation a non-neutralized beam (2 kV voltage depression) and a realistic RMS-spread of up to 8% for the transversal velocity of the beam have been considered. Table 2 shows the calculated values for the three different frequencies.

One of the most important challenges of the coaxial-cavity design is that the coaxial insert might be slightly misaligned with respect to the cavity wall, due to manufacturing tolerances. Depending on the magnitude of this misalignment, interaction efficiency, mode purity and/or mode stability are reduced, as are output power and reliability. Gyrotrons are welded and evacuated after assembly, thus one might be unable to fully compensate such an internal misalignment after bake-out. Therefore, one needs to define misalignment tolerances based on realistic simulations beforehand. In [25], possible effects of insert misalignment on the electron beam and the electromagnetic modes are discussed, and how to treat those effects numerically in interaction simulations.

With regard to the hollow-cavity concept, a systematic cavity design approach has been presented in [21]. Based on this approach and taking into account the operating frequency of 170.0 GHz for ITER as starting point the selected modes are $TE_{31,11}$ at 170 GHz, $TE_{37,13}$ at 204 GHz and $TE_{43,15}$ at 236 GHz. The modes at 170 GHz and 203 GHz were originally suggested and successfully tested by the JAEA gyrotron team [27]. This mode series has been extended

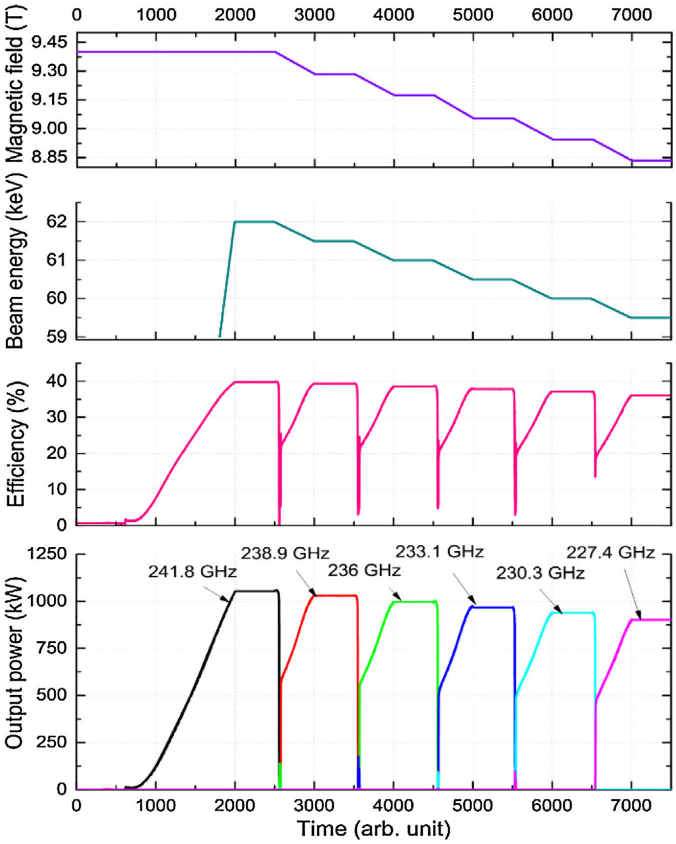

Fig. 3. Calculated magnetic field, beam energy, efficiency and output power for frequency step-tuning of the 236 GHz hollow-cavity gyrotron.

to 236 GHz and even 269 GHz. The relative caustic radii of all modes are nearly the same with only a small deviation of 0.08% from the average value. Consequently, the suggested mode series has a high rating in the scheme discussed in [23]. Using the EURI-CIDE code [28], time-domain self-consistent simulations have been conducted to verify the interaction performance of the selected mode series. For the main mode $TE_{43,15}$, 99 competing modes have been taken into account. Stable RF output of about 920 kW and an interaction efficiency of 36% have been achieved by assuming a moderate conductivity of $\sigma = 1.9 \cdot 10^7$ S/m.

In [29], the possibility for fast frequency step-tunability in leaps of 2–3 GHz steps is presented for the 236 GHz hollow-cavity gyrotron. The selection of the modes is restricted by the requirement that those modes shall couple appropriately, shall offer suitable frequencies, and their caustic radius should be nearly identical in order to have the same quasi-optical launcher design for all the selected modes.

Fig. 3 shows the calculated magnetic field, beam energy, efficiency and output power for frequency step-tuning from 242 GHz down to 227 GHz of the 236 GHz hollow-cavity gyrotron. Efficient MW-level operation is demonstrated for the selected modes. The simulation result shows a very high conversion efficiency for all selected modes in combination with the designed hybrid-type launcher [29]. Here, it has to be considered that the gyrotron operating frequency primarily depends on the operating magnetic field. The time required to move from one frequency to its neighbouring one is governed by the rate of change in the cavity magnetic field, hence, it is limited by the tuning capability of the superconducting (SC) magnet. So far, it is estimated that it will be possible to do a frequency step in the range of seconds.

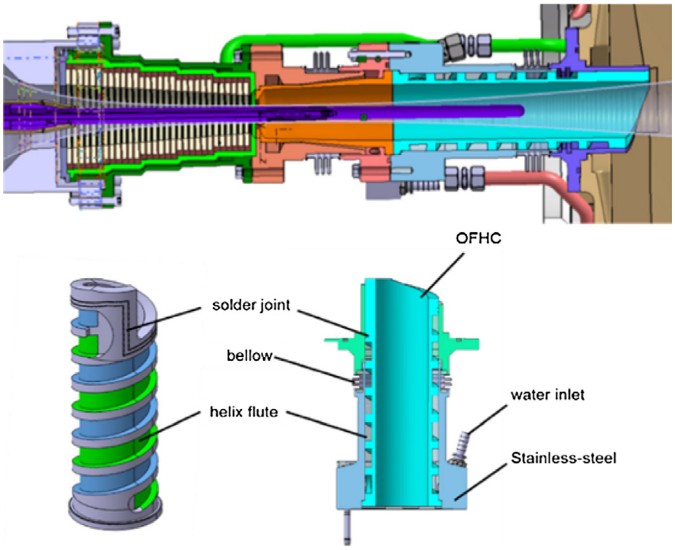

Fig. 4. Cooling concept for the major key components of a gyrotron mounted (top picture): beam tunnel, cavity and launcher; detailed cooling concept for the launcher (bottom picture).

2.2. Design of a modular, 2 MW, 1 s coaxial-cavity gyrotron pre-prototype

The theoretical considerations for the coaxial-cavity technology are supported by experimental campaigns to verify its superior performance [31,32]. In [33], the further development of a modular longer-pulse 2 MW 170 GHz gyrotron prototype is shown which includes an advanced water cooling system for beam tunnel, cavity and launcher. The main target of the project is to achieve a pulse length of 1 s while conserving the modularity of the gyrotron. Therefore, an independent water cycle of each key component is designed and verified with the multi-physics software COMSOL. Fig. 4 shows the cooling concept for the key components beam tunnel, cavity and launcher of the KIT modular design. It shows the detailed cooling concept for the launcher as well.

2.3. Investigation on CVD Diamond-Disc Brewster-angle window technology

Apart from an advanced fast-switching SC magnet, a proper broadband output window technology for continuous wave (CW) operation is mandatory for a frequency-tunable high-power fusion gyrotron. As mentioned before in the introduction, the transmission properties of a conventional single-disc window allow gyrotrons only to have operating frequencies at $f_N = (c/(2 \cdot d \cdot \sqrt{(\varepsilon_r)}) \cdot N = f_1 \cdot N)$ within a ±1 GHz frequency range. The CVD-diamond disc Brewster-angle window, which has a wide transmission band is a favourable option to achieve the frequency step-frequency tunability as demonstrated in [11,12]. Fig. 5 shows a Brewster-angle window mounted into a circular waveguide.

Today, a large axis of 140 mm can be technically realized for CVD-diamond discs. Assuming a Brewster-angle of 67.2°, the corresponding waveguide has a maximum diameter of 50 mm, which is sufficient for short-pulse, but not for high-power CW gyrotrons. A first target could be a diameter of 63.5 mm as used for the ITER waveguide, before approaching 80 mm as used for today's conventional output windows. In order to obtain windows with large diameter, an assembly technology is under investigation in which separately grown diamond parts are joined together, to create a mosaic disc. In particular, the manufacturing of an elliptical disc might be done by joining of total three parts. The main central part

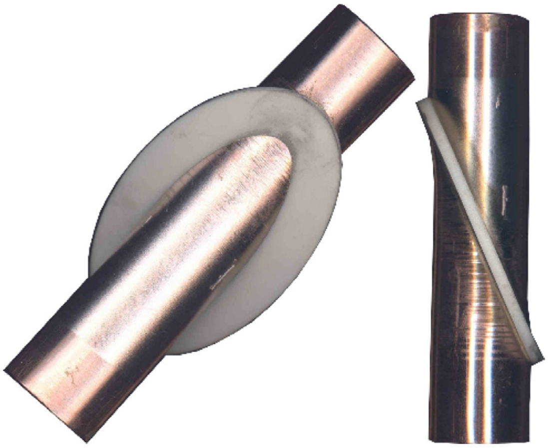

Fig. 5. CVD-diamond disc Brewster-angle window mounted into a circular waveguide (Brewster angle: 67.2°).

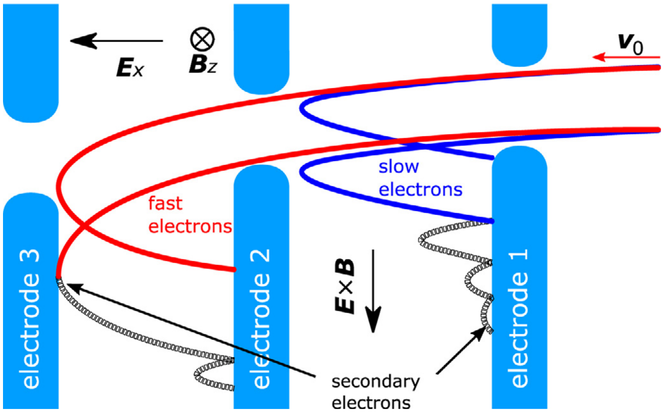

Fig. 6. $E \times B$ concept for multi-stage depressed collector technologies as proposed in [34,35]. The secondary electrons are always guided towards the electrodes of the collector (picture by C. Wu).

could be nearly cylindrical and might come from a cylindrical disc of 130 mm disc size. The two outer parts could be created from a disc of 90 mm size.

2.4. Investigation on multi-stage depressed collector (MSDC) technologies

Beside an output power of 2 MW, total efficiencies above 60% are required for a future DEMO to minimize the recirculating power. Single-stage depressed collectors allow a maximum recuperation efficiency of 60%. Hence, assuming an electronic efficiency of 35% for the gyrotron interaction, the total efficiency is limited to ~50%; thus, MSDCs are mandatory for future fusion gyrotrons. During collector development, three major problems have to be solved: the stray magnetic field of the SC magnet at the gyrotron collector; the returning of (secondary) electrons backwards to the cavity and the large spread of the kinetic energy of the electrons after the gyrotron interaction.

Several concepts for MSDCs are under investigation. As already mentioned, first theoretical approaches towards multi-stage depressed collectors have not yet been tested successfully [14–16]. Major reason can be the generation of secondary electrons, which deteriorate the performance of the gyrotron. A very promising approach has been published in [34]. This concept uses the $E \times B$ drift to sort and drift electrons towards electrodes with different decelerating potentials, according to the electrons' initial velocities. Fig. 6 shows the basic principle. Clearly, the issue of secondary electrons is solved as these electrons are always guided towards the electrodes, where they are generated and in the worst case, towards the previous electrode, but never back to the entry of the collector.

In order to apply the proposed $E \times B$ design approach, the transformation of the cylindrical hollow electron beam to one or more sheet beams is proposed using appropriate electrostatic and magnetostatic fields. A conceptual design for a MSDC system based on that idea is proposed in [35] which results in a collector efficiency of about 86%, resulting in total gyrotron efficiencies above 60%.

3. Conclusion

The R&D work within the EUROfusion PPPT WP HCD EC Gyrotron R&D and AD tasks is focusing on the theoretical feasibility and physical design of megawatt-class 240 GHz gyrotrons with a total efficiency of more than 60%. Frequency tuning in steps of around 2–3 GHz and multi-purpose operation at frequencies with intermediate leaps of about 30–40 GHz seems feasible. Both coaxial-cavity gyrotrons, with a possible output power around 2 MW, and conventional hollow-cavity gyrotrons, with above 1 MW, are under investigation. An additional experimental investigation shall verify the predicted operation capabilities for the coaxial-cavity technology. Several promising concepts for MSDCs are under investigation. The research and development are complemented by advancing the simulation and test tools capabilities significantly.

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References

[1] The Road to Fusion Electricity. ⟨https://www.euro-fusion.org/eurofusion/the-road-to-fusion-electricity/⟩, (Retrieved Sept. 26th, 2016).
[2] G. Federici, et al., Overview of EU DEMO design and R&D activities, Fusion Eng. Des. 89 (2014) 882–889.
[3] R. Wenninger, et al., Advances in the physics basis for the European DEMO design, Nucl. Fusion 55 (2015) 063003.
[4] C. Darbos, et al., Status of the ITER EC system, in: Proc. IEEE PPPS, San Francisco, USA, 2013, pp. P5–P22.
[5] E. Poli, et al., Electron-cyclotron-current-drive efficiency in DEMO plasmas, Nucl. Fusion 53 (2013) 013011.
[6] H. Zohm, et al., Where to locate DEMO in a one-step-to-an-FPP strategy, in: Proc. 43rd EPS Conf. on Plasma Physics, P4.077, 2016.
[7] J. Li, et al., Progresses and activities on the Chinese fusion engineering test reactor, in: Proc. 29th Symp. on Fusion Technology (SOFT), I2.2, Prague, 2016.
[8] D. Wagner, et al., Status of the new multi-frequency ECRH system for ASDEX Upgrade, Nucl. Fusion 48 (2008) 5.
[9] S. Alberti, et al., Progress on the upgrade of the TCV EC-system with two 1 MW dual-frequency gyrotrons, in: Proc. IRMMW-THz Conf., H5P.16.02, Copenhagen, 2016.
[10] T. Kobayashi, et al., Development of a dual frequency (110/138 GHz) gyrotron for JT-60SA and its extension to an oscillation at 82 GHz, in: EPJ Web of Conferences 87, 04008, 2015.
[11] G. Gantenbein, et al., First operation of a step-frequency tunable 1-MW gyrotron with a diamond Brewster angle output window, IEEE Trans. Electron Devices 61 (6) (2014) 1806–1811.
[12] A. Samartsev, et al., Efficient frequency step-tunable megawatt-class D-band gyrotron, IEEE Trans. Electron Devices 62 (7) (2015) 2327–2332.
[13] A. Gilmour, et al., Klystrons, Traveling Wave Tubes, Magnetrons, Cross-Field Amplifiers, and Gyrotrons, Artech House, Incorporated, Boston, 2011, ISBN: 978-1608071845.

[14] G. Ling, et al., A new approach for a multistage depressed collector for gyrotrons, IEEE Trans. Plasma Sci. 28 (3) (2000) 606–613.
[15] A. Singh, et al., Design of a multistage depressed collector system for 1-MW CW gyrotrons. I. Trajectory control of primary and secondary electrons in a two-stage depressed collector, IEEE Trans. Plasma Sci. 27 (2) (1999) 490–502.
[16] A. Singh, et al., Integrated design of depressed collectors for gyrotrons, IEEE Trans. Plasma Sci. 25 (3) (1997) 480–491.
[17] M. Thumm, State-of-the-art of high power gyro-devices and free electron masers, in: KIT Scientific Reports 7717, Karlsruhe, Germany, 2016.
[18] M. Thumm, et al., EU megawatt-class 140-GHz CW gyrotron, IEEE Trans. Plasma Sci. 35 (2) (2007) 143–153.
[19] T. Rzesnicki, et al., Experimental verification of the European 1 MW, 170 GHz industrial CW prototype gyrotron for ITER, in: 29th Symp. on Fusion Technology (SOFT), P3.025, Prague, 2016.
[20] B. Piosczyk, et al., A 2-MW, 170-GHz coaxial cavity gyrotron, IEEE Trans. Plasma Sci. 32 (3) (2004) 413–417.
[21] P. Kalaria, et al., Systematic cavity design approach for a multi-frequency gyrotron for DEMO and study of its RF behavior, Phys. Plasmas 23 (2016) 092503.
[22] M. Thumm, et al., Towards a 0.24-THz, 1-to-2-MW-class gyrotron for DEMO, J. TST 8 (3) (2015) 85–100.
[23] E. Borie, Review of gyrotron theory, in: Kernforschungszentrum Karlsruhe (KFK) Scientific Report 4898, KIT Scientific Publishing, Karlsruhe, Germany, 1991.
[24] J. Franck, et al., A generic mode selection strategy for high-order mode gyrotrons operating at multiple frequencies, Nucl. Fusion 55 (2015) 013005, 6pp.
[25] J. Franck, et al., Direct voltage depression calculation of arbitrary electron beams in misaligned coaxial gyrotron cavities, IEEE Trans. Electron Devices 63 (9) (2016) 3740–3746.
[27] K. Sakamoto, et al., 2013 IEEE Int. Vacuum Electronics Conference (IVEC), Paris, 2013.
[28] K.A. Avramides, et al., EURIDICE: a code-package for gyrotron interaction simulations and cavity design, in: 17th Joint Workshop on Electron Cyclotron Emission and Electron Cyclotron Resonance Heating (EC-17), EPJ Web of Conferences, vol. 32, 2012.
[29] P. Kalaria, et al., RF Behavior and Launcher Design for a Fast Frequency Step-tunable 236 GHz Gyrotron for DEMO, Frequenz, De Gruyter (2016), http://dx.doi.org/10.1515/freq-2016-0212.
[31] T. Rzesnicki, et al., 2.2-MW Record power of the 170-GHz European pre-prototype coaxial-cavity gyrotron for ITER, IEEE Trans. Plasma Sci. 38 (6) (2010) 1141–1149.
[32] T. Rzesnicki, et al., 2 MW, 170 GHz coaxial-cavity short-pulse Gyrotron – single stage depressed collector operation, in: Proc. Int. Conf. on IRMMW-THz, 2014, pp. 1–2.
[33] S. Ruess, et al., Ongoing developments for the KIT 2-MW 170-GHz coaxial cavity gyrotron prototype, in: VDE-ITG Workshop on Vacuum Electronics, 2016.
[34] I.Gr. Pagonakis, et al., A New concept for the collection of an electron beam configured by an externally applied axial magnetic field, IEEE Trans. Plasma Sci. 36 (2) (2008) 469–480.
[35] I.Gr. Pagonakis, et al., Multistage depressed collector conceptual design for thin magnetically confined electron beams, Phys. Plasmas 23 (2016) 043114.