Development of High-Power Microwave Vacuum Electronics at KIT

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ABSTRACT

The demand for megawatt-class gyrotrons for Electron Cyclotron Resonance Heating (ECRH) and plasma control in fusion devices is steadily increasing. At the same time, requirements on output power, efficiency, operational flexibility, reliability, and industrial manufacturability are becoming more stringent. KIT addresses these challenges as part of Europe's coordinated fusion research efforts.

Until 2024, research focused on gyrotrons for a prospective EU DEMO power plant operating at moderate magnetic fields (< 6 T), targeting frequencies of 170 GHz and output powers of up to 2 MW in continuous-wave (CW) operation. In parallel, KIT advanced gyrotron technologies for major fusion experiments such as Wendelstein 7-X (W7-X) [1] and ITER [2], and developed adapted variants of the W7-X gyrotrons for TCV (Switzerland) [3], CEA/WEST (France) [4], and GA/DIII-D (USA) [5].

Since 2024, emerging fusion start-ups have introduced concepts for compact fusion devices operating at substantially higher magnetic fields, which require gyrotrons at frequencies above 200 GHz. In Germany, this development is driven by Proxima Fusion with its Proxima Alpha and Stellaris projects [6]. Proxima Alpha requires gyrotrons operating at 238 GHz with output powers exceeding 1 MW. Within the BMFTR project HeatQIS (launched at the end of 2025), KIT, Proxima Fusion, and Diamond Materials GmbH & Co. KG are jointly developing suitable gyrotrons, diamond windows, and launcher components. A first industrial gyrotron, manufactured by Thales (France), is scheduled for testing at KIT by 2029.

In parallel, building on earlier developments of 1.5 MW gyrotrons for W7-X, KIT and IPP are working within the BMFTR project HiPMiB on a 2 MW version of the 140 GHz gyrotron for Wendelstein 7-X. This system is also targeted for industrial realization by Thales, with testing planned for early 2029.

Looking ahead, future fusion devices may operate at even higher magnetic fields (e.g., SPARC) [7]. Besides the development of stronger magnets, operation at the second harmonic of the electron cyclotron frequency represents a promising alternative. Within a EUROfusion Enabling Research activity, KIT and NKUA are investigating corresponding high-efficiency gyrotron concepts [8]. Achieving overall efficiencies of $\geq 60\,\%$ will require the implementation of multistage depressed collectors (MDCs). KIT has longstanding expertise in E×B-type MDCs, has already presented the design, manufacture and first test of a first short-pulse prototype, and is currently advancing both theoretical and experimental work toward CW-capable systems [9].

Beyond fusion-related high-power gyrotrons, KIT is also pursuing the development of gyrotron traveling-wave tubes (gyro-TWTs) for applications such as space radar. In collaboration with Fraunhofer FHR, a joint research group has been established. Furthermore, within the DFG Collaborative Research Center "HyPERiON", KIT is developing a 263 GHz, 1 kW gyro-TWT amplifier for DNP-NMR spectroscopy, with a first prototype planned in the current funding phase.

This presentation provides a comprehensive overview of KIT's activities in high-power microwave vacuum electronics, covering both fusion and non-fusion applications.

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