New trends of gyrotron development at KIT:

An overview on recent investigations

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Since many years KIT is strongly involved in the development of high power gyrotrons for use in ECRH. KIT is pursuing two development lines: (i) the conventional, hollow cavity gyrotron and (ii) the coaxial cavity gyrotron. KIT is pushing conventional cavity gyrotrons from 1 MW to 1.5 MW in a common project with IPP Greifswald. Coaxial cavity technology having the advantage of higher power capability, in particular at higher frequency, is used for the 2 MW 170 GHz short-pulse prototype. This gyrotron is currently being upgraded to allow pulse extension up to approximately 100 ms and up to 1 s in a second step.

For a future DEMOnstration fusion power plant two challenging trends with respect to gyrotron features are recognized: (a) the operating frequency will be above 200 GHz and (b) the requested total efficiency of the gyrotron should be higher than 60%. KIT is addressing these requirements by investigating both gyrotron technologies for their performance at a frequency well above 200 GHz. We started careful analysis of multi-staged-depressed collectors.

Keywords: Electron-Cyclotron-Resonance Heating and Current Drive, gyrotron, coaxial cavity, magnetron injection gun

1. Introduction

KIT is focusing on the development of gyrotron oscillators and related components for Electron Cyclotron Resonance Heating (ECRH) and Current Drive (CD) of magnetically confined nuclear fusion plasmas. It includes developments for ITER, W7-X and future DEMO.

KIT is heavily pushing the coaxial cavity gyrotron technology since this concept has several advantages compared to the hollow cavity technology and could be considered as the basis for future developments which will require higher output power per tube at higher operating frequency.

Since W7-X was started recently very successful with a 10 MW ECRH system the power upgrade of this system is considered. Based on the 140 GHz, 1 MW series gyrotrons developed at KIT and produced by European industry (Thales Electron Devices, France), the design of a 1.5 MW gyrotron has been initiated.

Within EUROfusion, the focus is on investigations towards a possible multi-frequency gyrotron for an EU DEMO. Although the design of this machine is under discussion and basic parameters are not yet fixed, some trends are clear: higher operating frequency (up to 240 GHz considered), higher output power per unit and highest efficiency. With the new FULGOR gyrotron teststand KIT is well prepared to address these questions. This contribution reports on progress with the 170 GHz, 2 MW coaxial cavity gyrotron, 140 GHz, 1.5 MW conventional cavity gyrotron and on gyrotron development activities in the > 200 GHz range.

2. Modular 170 GHz, 2 MW coaxial cavity gyrotron

Future fusion power plants call for high RF output power, efficiency and operating frequency which are beyond the state-of-the-art. KIT is addressing these questions with the development of advanced gyrotron concepts, namely the coaxial cavity gyrotron technology which uses an additional inner conductor for reduced mode competition and reduced voltage depression of the electron beam. The nominal operating parameters of the KIT 170 GHz, 2 MW coaxial-cavity pre-prototype are summarized in Table 1 [1].

As a first step towards a long-pulse/CW gyrotron, the modular gyrotron prototype was refurbished by introducing cooling systems for the beam tunnel, cavity, quasi-optical system, output CVD diamond window and collector [2]. The goal of this first step is to achieve a pulse length up to 100 ms. This configuration will allow a pre-validation of the gyrotron components thermal loading in CW operation. For the first time it will allow us the monitoring of the internal losses and of the energy balance of the coaxial tube during long-pulse operation.

Table 1. Operating parameters of the KIT coaxial-cavity pre-prototype gyrotron.

Operating cavity mode	$TE_{34,19}$
Frequency, f	170 GHz
RF output power, P_{out}	2 MW
Beam current, I_B	75 A
Accelerating voltage, V_C	90 kV
Velocity ratio (pitch factor), α	~ 1.3
Cavity magnetic field, B_{cav}	6.87 T
Efficiency with SDC	> 50 %

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Due to the modular design it is possible to implement and test new subcomponents with improved geometries, material compositions and even more advanced cooling systems very simply. Fig. 1 shows the assembled pre-prototype tube before and after installation into the superconducting (SC) magnet.

Fig. 1. The KIT 2 MW coaxial-cavity longer-pulse gyrotron (left). Gyrotron installed in the superconducting magnet (right), ready for experiments.

The gyrotron performance will be tested in two phases using two different electron guns. In the first phase the gyrotron will be equipped with the old diode electron gun, used already for the experiments with the SP pre-prototype gyrotron in the past [1]. This will provide as a reference for tests with a new triode gun, with an edge-coated emitter which should improve the quality of the electron beam.

With the old diode electron gun the nominal cavity mode $TE_{34,19}$ was excited at 169.9 GHz with an output RF power close to 2.1 MW and efficiency slightly above 30 % (in non-depressed collector operation), at nominal operating parameters (see Fig. 2). Additional optimization of the magnetic field and increasing the beam current to 80 A, raised the RF output power to 2.2 MW, with the efficiency close to 33 %.

The new triode gun has been designed by KIT and manufactured by THALES as industrial partner. Simulations show that the non-emissive coating at the edge-rims of the emitter should prevent electrons from

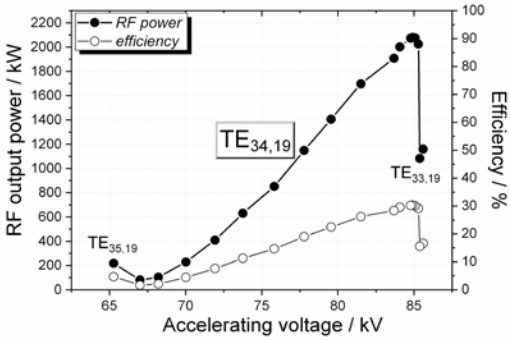

Fig. 2. Measured RF output power and output efficiency as a function of accelerating voltage without depressed collector.

that region. Those electrons suffer from a high pitch factor which may result in reflection of electrons in the cavity region resulting in beam instabilities [3]. First tests of this gun are on-going.

3. 140 GHz, 1.5 MW gyrotron for W7-X

Motivated by the successful start of W7-X [4] with its ECRH system consisting of ten 1 MW gyrotrons, studies were started on a power upgrade of the gyrotron to 1.5 MW in CW operation with the option for MW-class operation also at 175 GHz to be used for Collective Thomson Scattering (CTS) diagnostics. Based on the existing European gyrotron design it was found that the most promising development path would be to operate in the modes $TE_{28,10}$ at 140 GHz and $TE_{36,12}$ at 175 GHz.

Cavity and non-linear uptaper have been designed for the upgraded gyrotron, to allow for 1.5 MW of output power with the $TE_{28,10}$ mode at 140 GHz. The performance of the non-linear uptaper, in terms of mode conversion, has been validated numerically. The calculated mode conversion is minor, resulting in 99.87% transmission for the 140 GHz $TE_{28,10}$ mode and 99.81% transmission for the 170 GHz $TE_{36,12}$ mode.

The performance of the cavity and the non-linear uptaper, in terms of beam-wave interaction, has also been numerically validated using the code-package EURIDICE [5]. In the simulations realistic assumptions on electron velocity ratio (α), magnetic field profile and spreads in electron energy, α, and beam radius have been included.

The operation at 140 GHz, assuming a maximum magnetic field of 5.55 T, is illustrated in Fig. 3. During start-up, a series of modes is excited before the excitation of the operating $TE_{28,10}$ mode which reaches the nominal operating point (V_b = 78.5 kV, I_b = 56 A, α = 1.3) where it delivers 1.68 MW of microwave power at the end of the non-linear uptaper with an interaction efficiency of 39.5 %. Assuming the typical 5% additional losses until the gyrotron window, this corresponds to 1.6 MW of power at the window. For the operation at 175 GHz, a maximum magnetic field of 7.05 T is assumed. If a careful electron gun design and a

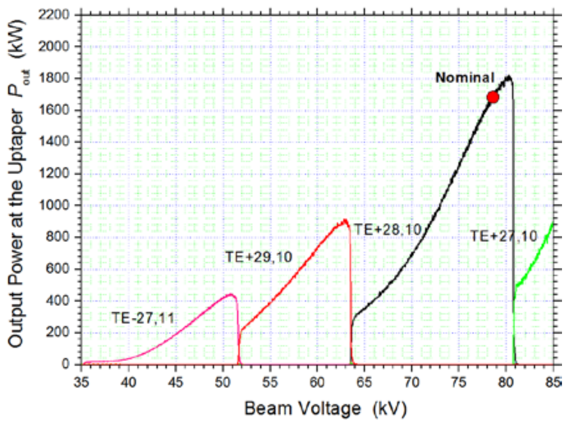

Fig. 3. Multi-mode simulation (36 competing modes) of the diode start-up for gyrotron operation at 140 GHz. A negative azimuthal index denotes a counter-rotating mode.

magnet that permits some control over the amplitude and angle of the magnetic field vector in the gun region is applied, 1.16 MW RF output power at the nominal operating point is obtained.

A quasi-optical launcher of the hybrid type [6] has been designed, taking into account the possibility for operation both at 140 GHz and 175 GHz. Operation in the $TE_{28,10}$ mode at 140.0 GHz produces a microwave beam with a Gaussian mode content of 97.4% at the launcher aperture. For operation with the $TE_{36,12}$ mode at 175.4 GHz, the corresponding Gaussian mode content is 95.3%.

To perform low-power tests of the quasi-optical mode converter and mirror system of the gyrotron (launcher & mirrors) a mode generator has been designed and built, based on [7].

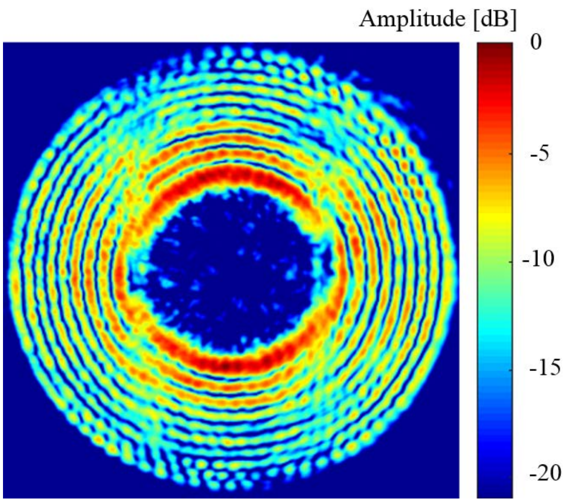

Fig. 4. Measured normalized pattern (electric field amplitude) of the $TE_{28,10}$ mode at 140.155 GHz.

The frequency of the $TE_{28,10}$ mode and of the $TE_{36,12}$ mode in the mode generator cavity was found to be 140.155 GHz and 175.992 GHz, respectively. The mode pattern (electric field amplitude) has been measured using stepwise scanning of a pick-up antenna with a resolution in the plane of measurement of 0.2 mm × 0.2 mm. Figure 4 shows the pattern of the $TE_{28,10}$ mode at 140.155 GHz. The results are in very good agreement with the simulations.

4. R&D towards EU DEMO

ECRH systems for future **Demo**nstration power plants (DEMO) or **F**usion **P**ower **P**lants (FPP) will most probably require multi-megawatt and continuous wave gyrotrons which are able to oscillate at a frequency significantly above 200 GHz [8]. To benefit from the basic advantages of the coaxial cavity technology and to profit from the existing experience on this technology at KIT the 2 MW 170 GHz gyrotron has been taken as a starting point for a 170/204/238 GHz multi-frequency gyrotron design study [9]. One of the goals of this activity is to show that efficient operation at these frequencies is possible in the frame of the KIT FULGOR gyrotron test facility with a 10.5 T SC magnet.

For optimum mode and frequency selection two important aspects have to be addressed:
1) Minimisation of reflections at the window: The operating frequencies should correspond to the natural resonances of the output diamond window using:
$f_{op} = (N \cdot c_0) / (2 \cdot d_{window} \cdot \varepsilon_r^{1/2})$, $N \in \mathbb{N}$, where c_0 is given by the speed of light, d_{window} by the thickness of the window and ε_r by the permittivity of the window material (e.g. CVD diamond).
2) Optimum operation of the launcher and quasi-optical system: The difference of the caustic radius of the modes should be within <3-4%, where the caustic radius is determined by: $R_C = m \cdot R_o / \chi_{m,n}$, R_o is the cavity radius and $\chi_{m,n}$ the eigenvalue which is given by the p^{th} root of the characteristic equation [6]. This condition enables the usage of the existing, or at least of a similar, quasi-optical system.
Taking these considerations into account it was found that the $TE_{40,23}$ mode operating at 204 GHz and the modes $TE_{48,26}$ and $TE_{46,27}$ operating at 237 GHz and 238 GHz, respectively, are most promising to be operated with the 170 GHz $TE_{34,19}$-mode gyrotron. Table 2 summarizes the properties in terms of window reflection and caustic radius of the chosen modes. Detailed numerical simulations are ongoing to clarify the acceptable difference in caustic radius and the conversion efficiency of the quasi-optical output coupler.

Table 2. Mode Selection for Multi-Frequency Operation.

Mode	$TE_{34,19}$	$TE_{40,23}$	$TE_{48,26}$	$TE_{46,27}$
Frequency [GHz]	170.0	204.179	237.242	238.351
Window reflection [%]	0	0.026	0.472	0.101
Rel. caustic radius	0.3232	0.3167	0.3270	0.3119
Diff. in caustic radius [%]	0	2.01	1.18	3.62

The beam-wave interaction code EURIDICE [5] has been used to study the performance at the frequencies under discussion. As a reference for the profile of the magnetic field a new SC magnet, ordered within the FULGOR project at KIT and delivered by TESLA company in 2019, has been assumed.

As a typical example Fig 5 shows the start-up scenario for 204 GHz operation assuming a cavity with reduced length in order to meet the requirements on cavity wall loading (< 2 kW/cm^2). The operation point is defined by U_{beam} = 86.5 keV and I_{beam}= 75 A, having a RF output power of 2.06 MW and an interaction efficiency of 32.3%. Due to the technical limits on wall loading in the cavity operating points with higher output power are not accessable in long pulse operation.

The operating modes excited in the cavity are converted into the fundamental Gaussian mode using an internal quasi-optical mode converter which contains a mirror-line launcher and three mirrors. The mirror-line launcher is highly tolerant to fabrication errors on the wall contour. The simulation results show that in the case of an uncertainty of the wall perturbation of ± 10 μm, the launcher will still provide an RF beam with high Gaussian mode content. The new, optimised mirror-line launcher has been designed for the operating frequencies 170 and 204 GHz [10]. Simulations show a Gaussian mode content of 97.2 % at 170 GHz and 96.6 % at 204 GHz.

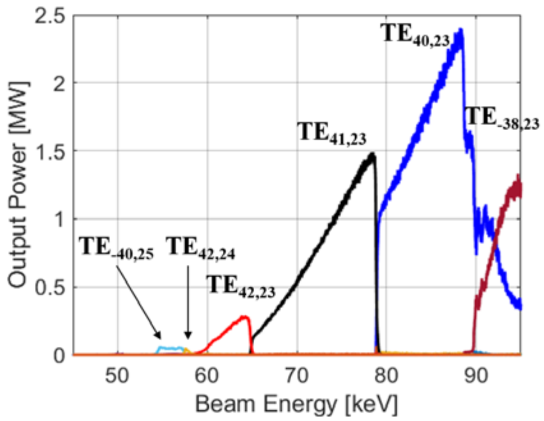

Fig. 5. Realistic start-up scenario in an optimized cavity of $TE_{40,23}$ at B= 8.23 T and I_{beam} = 75 A.

With increasing the installed power of an ECRH system and increasing the pulse length up to CW, efficient operation of gyrotrons becomes more and more important. Gyrotrons operating with single-stage depressed collectors achieve an overall efficiency of 50-55 %. With the concept of multistage depressed collector (MDC) systems a further increase of the overall gyrotron efficiency is possible. Although MDC is state-of-the-art for conventional travelling wave tubes, it is still a challenge for a high power gyrotron with a strong magnetic field and a powerful electron beam. A possible design is the so-called E×B drift concept as shown in Fig. 6.

Several theoretical design approaches based on the E×B drift have been recently published [11, 12]. Efficient sorting of the magnetically confined gyrotron electron beam to the different electrodes is a big advantage of this concept. In that first investigation, a theoretical design was proposed for the demonstration of the E×B drift concept. The collector efficiency was estimated to be of the order of 91 %. This study used an ideal situation with

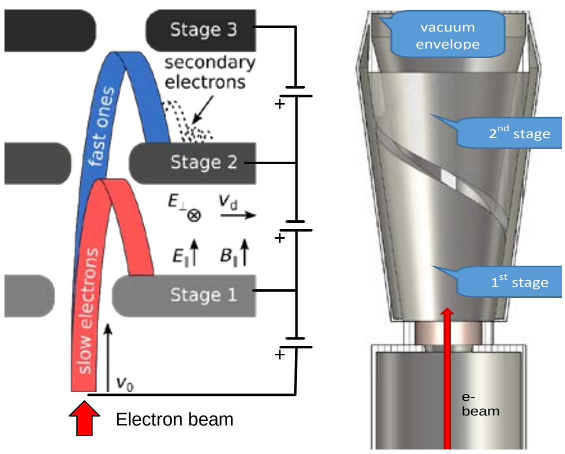

Fig. 6. Design principle of the E×B drift MDC concept (left) and a proposal with helical electrodes (right).

an infinite number of electrodes was considered due to limitations of the simulation tool. Figure 6 shows a so-called helical MDC which bases on the E×B concept as earlier proposed in [12]. In [13], advanced concepts of this type of MDC are numerically investigated with a full three dimensional simulation tool. MDCs with two, three and four stages have been optimized for a spent beam of a high power gyrotron. High efficiency has been demonstrated for a variety of realistic spent beam energy distributions with negligible reflected current.

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References

[1] T. Rzesnicki, et al., *IEEE Transactions on Plasma Science*, **38**, 1141-1149, 2010.

[2] S. Ruess, et al., *International Journal of Microwave and Wireless Technologies*, DOI: 10.1017/S1759078718000144.

[3] I. Gr. Pagonakis, et al., 43rd International Conference on Infrared, Millimeter and Terahertz Waves, Proceedings, 2018.

[4] R. C. Wolf *et al*., Nucl. Fusion **57**, 102020 (2017)

[5] K. A. Avramides, et al., EPJ Web of Conf. **32**, 04016 (2012)

[6] J. Jin, et al., IEEE *Trans. Microwave Theory and Techniques* ***65***, *699*-706 (2017**)**

[7] N. L. Alexandrov, et al., Int. J. Infrared and Millimeter Waves, **13**, 1369-1385, 1992.

[8] J. Jelonnek, et al., EPJ vol. 147, 2017

[9] T. Ruess, et al., 20th Joint Workshop on Electron Cyclotron Emission (ECE) and Electron Cyclotron Resonance Heating (ECRH), Proceedings, 2018.

[10] J. Jin, et al., *IEEE Transactions on Microwave Theory and Techniques*, **57**, 1661-1668, 2009.

[11] I. Pagonakis, et al., Phys. Plasmas, **23**, 4 (2016)

[12] C. Wu, et al., Phys. Plasmas, **25**, 033108 (2018)

[13] B. Ell, et al., 20th Joint Workshop on Electron Cyclotron Emission (ECE) and Electron Cyclotron Resonance Heating (ECRH), Proceedings, 2018.