28th IAEA Fusion Energy Conference (FEC 2020)

Contribution ID: **1142** Type: **Regular Poster**

High power gyrotron development for advanced fusion devices

Friday 14 May 2021 12:10 (20 minutes)

Introduction
Gyrotron oscillators and related components for Electron Cyclotron Resonance Heating (ECRH) and Current Drive of magnetically confined nuclear fusion plasmas are a major development at KIT. These activities include both, coaxial cavity gyrotron technology and conventional hollow cavity technology. Although hollow cavity 1 MW-class gyrotrons are widely used, mature and achieved industrial state-of-the-art, coaxial cavity gyrotron technology offers better performance towards even higher output power and higher operating frequency.
In the frame of upgrading the ECRH system of W7-X, the development and manufacturing of a 1.5 MW, 140 GHz short pulse gyrotron has been started. We will present the design of the tube and first experimental results.
Progress has been made with a modular, short pulse 2 MW, 170 GHz coaxial cavity gyrotron which is step by step upgraded to allow a pulse length of up to several 100 ms.
ECRH systems for future power plants (e.g. DEMO) will require multi-megawatt and continuous wave gyrotrons with an operating frequency which is probably significantly above 200 GHz. In the R&D it is addressed with a multi-frequency design of the coaxial cavity gyrotron allowing 170 GHz, 204 GHz and 238 GHz operation (at a later stage). These experiments will be performed with the new KIT gyrotron teststand FULGOR which includes a superconducting magnet, capable of a magnetic induction of up to 10.5 T.

1.5 MW, 140 GHz gyrotron –design and first results of a short pulse prototype
The outstanding results of the first W7-X experimental periods motivated and showed the necessity to upgrade the existing ECRH system. It is planned to increase the gyrotron unit power from 1 to 1.5 MW at 140 GHz in CW operation. Based on the existing 1 MW, 140 GHz gyrotron, KIT is developing and manufacturing a short pulse pre-prototype gyrotron to verify the physics design of the gyrotron. In parallel IPP ordered an industrial CW gyrotron at the European manufacturer, THALES, Velizy, France, which is based on the short pulse tube design.
The electron gun has been redesigned with minor modifications of the contour of the cathode nose and prolongator, however, keeping the emitter ring identical. Optimised ceramics material will be used in the beam tunnel in order to allow a parasitic mode-free operation at the nominal beam current of 55 A. Thus, the improved beam tunnel exhibits 60 % higher losses and 3 times fewer dangerous modes compared to the existing one.
Cavity and non-linear uptaper have been designed to allow for 1.5 MW of output power with the TE28,10 mode at 140 GHz. The calculated mode conversion in the uptaper is vanishing, resulting in 99.87 % transmission for the 140 GHz TE28,10 mode.

Fig. 1: Schematic of the quasi-optical system (left) and low power measurement of the RF beam (right) of the TE28,10 mode gyrotron (logarithmic scale).
A mirror-line launcher and three mirrors with quadratic surface contour functions for the conversion of the operating TE28,10 mode to a Gaussian RF beam at the gyrotron window have been designed. The simulations show a very high TEM00 mode content at the window and a very low stray radiation level. A schematic of the quasi-optical system is shown in Fig. 1. A first low power measurement using a mode generator showed an excellent agreement with the simulations.
The construction of the short-pulse gyrotron will be finalised in spring 2020 and experiments will immediately start.

2 MW, 170 GHz coaxial cavity gyrotron for 100 ms operation
The use of a coaxial insert with longitudinal corrugations supports single-mode oscillations and suppression of competing modes in a highly oversized cavity. Applying coaxial cavity technology allows to develop very high-power gyrotrons at very high operating frequencies. KIT is working in this field since several years with the goal to develop a modular pre-industrial 2 MW, 170 GHz gyrotron with a pulse length of up to several 100 ms. This development is based on the existing 2 MW, 170 GHz coaxial cavity gyrotron operating in the TE34,19 mode [1].
The basic configuration has been upgraded by active water cooling systems for the beam tunnel, cavity, mirror box and collector and the tube has been baked out in a N2 furnace at a temperature of up to 350 °C for 2 weeks. Thus, very good vacuum conditions were obtained (~10-10 mbar). First experiments with the goal to achieve a pulse length of up to 100 ms have been started.

170/204 GHz 2 MW Development for DEMO
To benefit from the basic advantages of the coaxial cavity technology and to profit from the existing experience on this technology at KIT the TE34,19 mode 2 MW 170 GHz gyrotron has been taken as a starting point for a 170/204/238 GHz multi-frequency gyrotron design study. 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.
The TE40,23 mode has been selected for 204 GHz operation at B~ 8.23 T. Realistic interaction simulations have shown that a RF power of up to 2 MW can be produced. First investigations on the operation at 238 GHz in the TE48,26 mode at B~9.45 T have been started. A multi-frequency launcher and and 3-mirror system has been designed to couple efficiently the cavity modes to the fundamental Gaussian beam. Recent simulations have shown that a Gaussian mode content of 96.6 % (204 GHz) and 97.3 % (170 GHz) can be achieved. In order to verify these results a low-power test set-up has been manufactured and first experiments have been performed to generate the TE40,23 cavity mode at 203.95 GHz (see Fig. 2).
Conclusions
To meet the needs of reliable and powerful ECRH systems KIT is continuously progressing in the development of gyrotrons. Based on the successful 1 MW 140 GHz gyrotron for W7-X, a conventional 1.5 MW gyrotron has been investigated and manufactured. First results of a short pulse gyrotron will be expected in Q2 2020.
The coaxial cavity gyrotron will be developed in two directions: increased pulse length of the existing modular 170 GHz, 2 MW gyrotron towards several 100 ms and multi frequency capability towards 204 GHz and 238 GHz. First tests with increased pulse length will be shown.

Acknowledgement
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.
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Session Classification: P7 Posters 7

Track Classification: Fusion Energy Technology