Quasi-Optical Mode Generator for Excitation of Very High-Order Modes up to 240 GHz

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***Abstract*—A new quasi-optical mode generator setup has been designed to excite the $TE_{48,26}$ mode operating at 238 GHz. It will be the mode with the highest eigenvalue ($\chi_{48,2}$ = 146.80) ever measured in cold tests and therefore the successor of the $TE_{40,23}$ mode operating at 204 GHz. In this paper, the design of the new coaxial cavity for the mode generator setup is presented, which is based on the cavity design of the corresponding gyrotron. Simulations using a scattering matrix code show a mode purity of 99.5 % at the output of the cavity at an operating frequency of 238.101 GHz. Recently, the main components are under manufacturing. After delivery mid-2024, first experiments will be performed.**

Keywords—quasi-optical, mode generator, high-order modes, high frequency test systems

I. Introduction

A gyrotron is an electron vacuum tube delivering an output power in the Megawatt-range at frequencies exceeding 100 GHz. This unique capability is essential for Electron Cyclotron Resonance Heating and Current Drive (ECRH&CD) systems employed in nuclear fusion devices that rely on magnetically confined plasmas. Gyrotrons act as oscillators, by exploiting the interaction between a weakly relativistic electron beam and a transverse electric cavity mode. The use of high-order rotating transverse electric ($TE_{m,p}$) cavity modes in significantly oversized waveguides allows the reduction of wall loading within the cavity. However, these high-order rotating $TE_{m,p}$ modes are less suitable for transmission through a waveguide or quasi-optical transmission line over distances of 60-100 m to fusion machines, such as Wendelstein 7-X in Greifswald, Germany [1], ASDEX Upgrade in Garching, Germany [2], as well as future ITER in Cadarache, France [3] and EU DEMO [4]. Consequently, the operating cavity modes are transformed into fundamental Gaussian TEM_{00} output beams through an internal quasi-optical output coupler system. In the European gyrotrons, this system consists of a launcher and three mirrors, followed by a vacuum window and a Matching Optics Unit (MOU). The verification of the quasi-optical output coupler system is a critical step before its installation into the gyrotron, because the components cannot tolerate design failures and accept manufacturing tolerances of only a few micrometers for proper operation. The verification process, known as "cold measurements", is conducted outside the gyrotron and without the use of an electron beam. To verify the quasi-optical output system, the relevant operating cavity modes are first excited using a quasi-optical mode generator [5]. After the successful excitation of the high-order rotating cavity modes, the quasi-optical output coupler is thoroughly examined for confirmation. The excitation and validation of the $TE_{40,23}$ mode at 204 GHz has been presented in [6]. It is the mode with the highest eigenvalue ($_{0,2}$ = 126.34) ever excited in cold measurements, yet. In this paper the design of a new quasi-optical output system is presented for the $TE_{48,23}$ mode operating at 238 GHz and having an eigenvalue of ($\chi_{48,26}$ = 146.80).

II. Quasi-Optical Mode Generator

A photo of a quasi-optical mode generator is depicted in Fig. 1. It consists of a rectangular-to-circular waveguide transition and a Potter horn, where the $TE_{1,0}$ fundamental rectangular waveguide mode is transformed into a Gaussian beam, $TEM_{0,0}$ mode. This mode is launched as a spherical wave onto a set of Teflon lenses. The Teflon lenses form an astigmatic Gaussian-like beam that is then focused onto a quasi-parabolic (q.-p.) mirror. The astigmatism is used to minimize spillover losses on the q.-p. mirror. Two high-precision linear drivers and a goniometer are used to adjust the q.-p. mirror for ideal focusing of the beam into the cavity. The linear drivers are used to adjust the q.-p. mirror vertically and horizontally, and the goniometer is used to adjust the tilt. The focused beam penetrates through the thin cavity wall, which is perforated with cut-off holes [7] and excites the resonant cavity mode. The cavity is specifically designed for low-power testing using a scattering matrix code [8]. An additional non-linear up-taper is attached to the cavity of the mode generator to increase the spatial resolution of the field measurement. The field pattern is assessed at the end of the non-linear up-taper using a chamfered rectangular standard waveguide receiving antenna. The receiving antenna is mounted on a 3D measurement arm that performs a stepwise scan. The resulting signal is analyzed by PNA series vector network analyzer (VNA). Extension modules are installed to cover the frequency range from 220-330 GHz.

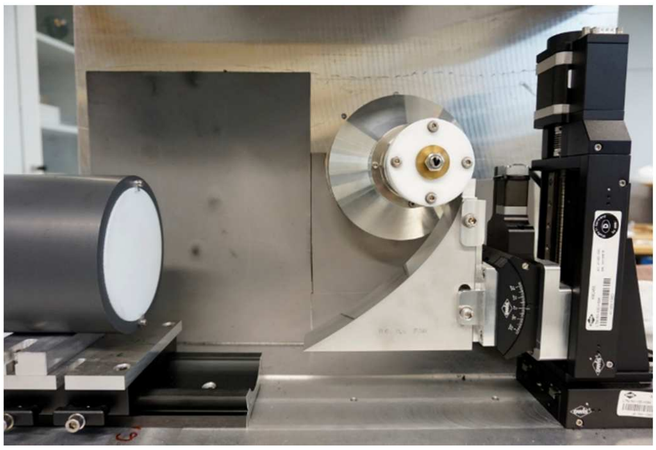

Fig. 1) Photo of a quasi-optical mode generator set-up with a lens system, a quasi-parabolic mirror, high-precision linear drivers and a coaxial-cavity.

A. Design of a Quasi-Optical Mode Generator at 238 GHz

A very precise design and adjustment of the mode generator is mandatory because of the increasing number of modes that can propagate with increasing frequency. The number of propagating modes N in a circular waveguide can be calculated approx. using $N = 2.55 \cdot (2R_o/\lambda_0)^2$, where R is the radius of the midsection of the cavity and λ_0 the free space wavelength. N = 5600 for a radius of 29.55 mm at 238 GHz. A new design for a cavity with coaxial insert has been developed based on the cavity design used for the $TE_{40,23}$ mode operating at 204 GHz [9]. The insert radius R_i is chosen, according to the eigenvalue spectrum presented in Fig. 2, to separate the eigenvalue and therefore the resonant frequency of the $TE_{48,26}$ mode from neighboring modes with similar field structures, by reducing the mode competition of the main mode with its competitors. The calculated eigenfrequency of the selected mode is 238.101 GHz and the quality factor is 4423. The calculated mode purity at the end of the cavity is over 99.5 %. However, the physical size of the receiving antenna allows only a low resolution at the end of the cavity and thus cannot accurately resolve the field distribution. Therefore, a non-linear up-taper is considered in the simulation. The mode purity is reduced to 97 % using an already existing 1540 mm long non-linear up-taper due to mode conversion. The calculated vertical polarized field intensity pattern of the $TE_{48,26}$ mode is presented in Fig. 3.

B. Manufacturing Process

The perforated coaxial cavity is the most challenging part in the manufacturing step. The thin outer wall combined with the perforation makes the cavity to a very sensitive component in terms of mechanical robustness. The small cut-off holes are cut by laser achieving a high manufacturing accuracy of less than 10 µm in a moderate time for around 4000 required holes. Besides the cavity, also an insert, a quasi-parabolic mirror, a set of Teflon lenses and a Potter horn are manufactured.

C. Experimental Verification up to 240 GHz

The manufactured components are expected to be delivered by mid-2024. After installation, the first experiments for exciting the $TE_{48,26}$ mode at 238 GHz will be performed using the automatized mode generator setup [10] and will be presented.

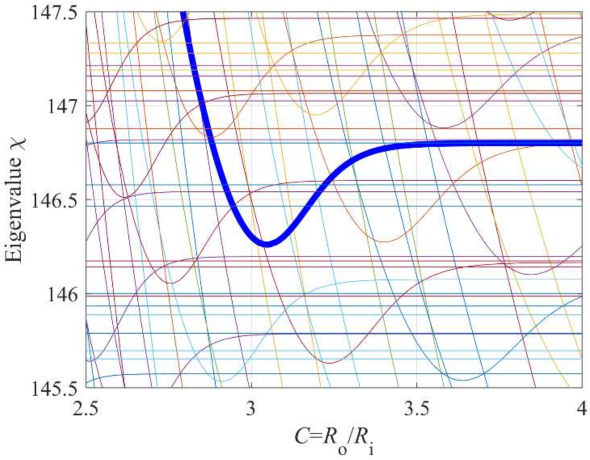

Fig. 2: Eigenvalue spectrum. The eigenvalue curve for the $TE_{48,26}$ mode is highlighted in blue.

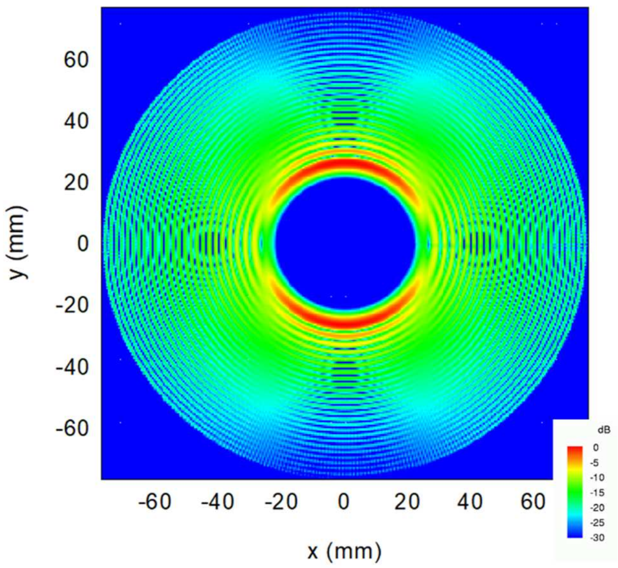

Fig. 3) Depiction of the simulated vertical polarized field intensity pattern of the $TE_{48,26}$ mode operating at 238.101 GHz

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