Theoretical Investigation on Possible Operation of a 140 GHz 1 MW Gyrotron at 175 GHz for CTS Plasma Diagnostics at W7-X

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Abstract - Collective Thomson Scattering (CTS) is a common diagnostic technique for ion temperature measurements in experimental fusion plasma reactors. Such a system was successfully installed and commissioned at the Wendelstein 7-X stellarator (W7-X). For this purpose, a 140 GHz gyrotron of the Electron Cyclotron Resonance Heating (ECRH) system was used as source of the required probing millimeter (mm)-wave beam. However, accurate measurements in the plasma core were not possible at this heating frequency due to the absorption of the mm-waves and the high electron cyclotron emission background. To suppress these effects and to enhance the accuracy of the measurements, it is required to increase the frequency of the probing beam. In this work, the possibility to operate the same gyrotron, which has its nominal operation at 140 GHz, at a higher frequency is comprehensively investigated.

I. Introduction

In experimental fusion reactors, diagnostic tools are very important to study the physics and behavior of the plasma.[1] Such a diagnostic tool is Collective Thomson Scattering (CTS), which allows measurements of ion temperature, fast ion velocity distribution function, isotope ratio, plasma rotation, etc.[2] For a CTS diagnostic system, a high power mm-wave source is needed. Gyrotrons are electron vacuum tubes, which are capable of high power generation from the mm- to sub-mm-wave regime[3] and are a suitable source for CTS diagnostics.

A CTS diagnostic for ion temperature measurements was installed and commissioned at the stellarator Wendelstein 7-X (W7-X).[4] For the probing beam of this CTS diagnostic, a gyrotron[5] of the Electron Cyclotron Resonance Heating (ECRH) system of W7-X,[6] which operates at 140 GHz, has been used. However, measurements in the plasma core at this frequency cannot be adequately accurate due to the absorption of the probe mm-wave beam and due to the high electron cyclotron emission (ECE) background,[7] which both deteriorate signal-to-noise ratio. For optimal CTS measurements in the plasma core, the frequency of the probing beam should be in the range in which ECE of the plasma is minimal.

At ASDEX upgrade, dual frequency gyrotrons are operated at 140 GHz for ECRH and at a lower frequency of 105 GHz to produce the probing beam for the CTS diagnostic.[8] Operation at such a frequency range has also been demonstrated by the 140 GHz W7-X ECRH gyrotron[5]. In particular, the gyrotron has been operated at a frequency of 103.8 GHz with an output power of 410 kW in 10 s pulses.

However, for the CTS diagnostic at W7-X, a significant higher frequency than the ECRH frequency shall be used for the probing beam to achieve more accurate measurement results. Although a frequency change to 105 GHz offers itself due to the already demonstrated W7-X gyrotron operation in this regime, it is not optimal for the CTS diagnostic at W7-X. It was determined that a change to a higher frequency range between 170 GHz and 185 GHz is more beneficial for the CTS diagnostic.[7] In contrast to tokamaks that have a Greenwald density limit and operate at relatively low densities and high temperatures, stellarators work at a different regime. Due to 1/ν transport and absence of the Greenwald density limit, stellarators operate at low plasma temperatures and high densities. For the case of W7-X, at the target central density of 1.5×10^{20} m^{-3}, it is practically impossible to place the overlap volume of the CTS diagnostic into the plasma core with a probing beam at 105 GHz. Moreover, the ECE background has a local minimum at the frequency range between 170 GHz to 185 GHz, which exceeds the ECE background at 105 GHz by an order of magnitude.[9]

In this work, the possibility to operate one of the gyrotrons of the W7-X ECRH system at a significant higher frequency and an output power in the range of 450 kW to be used as a probe for CTS measurements is investigated. Changing the operational frequency of a high power gyrotron is not a straightforward procedure. The W7-X gyrotron has been designed and optimized for operation at the frequency of 140 GHz. Therefore, operation of the gyrotron at a higher frequency has to be compatible with all gyrotron subcomponents.

In addition, a new magnet will be procured to generate the required higher magnetic field for operation at the higher frequency. The design of the new magnet will also ensure the generation of the nominal magnetic profile for operation at 140 GHz to secure the efficient operation of the gyrotron for ECRH.

The possible frequencies of the mm-waves, which can exit from the gyrotron tube, are limited by the thickness of the diamond output window. Furthermore, the requirement for microwaves at a different frequency implies that the gyrotron must operate at a different Transverse Electric (TE) mode than the nominal 140 GHz $TE_{28,8}$ mode. The higher frequency mode should be compatible with the quasi-optical output coupler (launcher and mirrors) of the gyrotron. In addition, it should be checked that an appropriate electron beam for the excitation and the efficient interaction in the cavity with the higher frequency mode can be generated by the Magnetron Injection Gun (MIG) of the 140 GHz gyrotron.

In this work, several candidate modes for operation at higher frequency are identified and their compatibility with all gyrotron subcomponents is theoretically investigated. Based on this analysis, the most appropriate mode is chosen. The operating parameters of the gyrotron required for an efficient operation at a higher frequency, based on the theoretical results, are presented.

This paper is organized as follow. In Section II, the gyrotron window and quasi-optical system are analyzed. Suitable candidate TE modes that are compatible with the window thickness are identified and their transformation into a Gaussian-like beam through the quasi-optical system is investigated. Depending on several criteria such as the beam location at the window, the reflectivity at the window and the Gaussian mode content, some of the candidate modes are discarded. In Section III, the electron gun and the generated electron beam are studied. Different operating points of the electron gun are investigated to find suitable electron beam parameters for the excitation of the candidate modes in the cavity. Those candidate modes for which no suitable beam parameters could be found are also discarded. In Section IV, the excitation in the cavity of each of the remaining candidate modes and possible mode competition is investigated. Finally, in the conclusion in Section V, the remaining candidate modes are presented and the most suitable TE mode for operation at 175 GHz is determined.

II. Window and Quasi-Optical System

The component that determines the possible operating frequencies of the gyrotron is the output window. The window should be as much as possible transparent to the generated mm-waves to minimize reflections which could influence the operation by increasing the internal stray radiation level.

The thickness d_w of the window disk is the parameter that determines the frequencies of the mm-waves which can be transmitted through the window. The relation between these frequencies and the window disk thickness is

$$f = n\frac{c_0}{2\sqrt{\varepsilon_r}d_\mathrm{w}}, \tag{1}$$

where c_0 is the free space speed of light, ε_r the relative dielectric permittivity of the disk and n is a positive integer. The synthetic diamond windows used in the 140 GHz W7-X gyrotrons have an ε_r of 5.67, a loss tangent of 2×10^{-5}, while the thickness d_w is 1.799 mm ($n = 4$). The next higher frequency for which the window is transparent is for $n = 5$, resulting in a frequency of 175 GHz, which is the choice for the CTS diagnostic.

In Figure 1, the reflectivity of the window of the W7-X gyrotron is calculated for different frequencies. The equations for the reflectivity at the window are presented in[10]. The reflectivity vanishes only for the frequencies given by Equation (1).

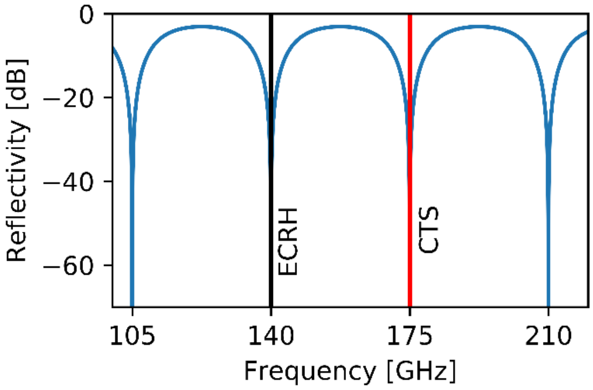


Figure 1: Reflectivity at the W7-X gyrotron window

The operation of the gyrotron at 175 GHz requires a different TE mode than the nominal TE$_{28,8}$ mode for the operation at 140 GHz. Several candidate TE modes were chosen based on the following criteria:

- The TE mode is excited in the cavity near its cut-off frequency $f_{\text{cut-off}}$. As shown in Figure 1, the reflectivity of the gyrotron window increases rapidly the farther away the frequency of the TE mode is from 175 GHz. Therefore, the cut-off frequency of a candidate mode should be close to 175 GHz.
- The caustic radius r_{caustic} of a candidate TE mode should be close to the caustic radius of the nominal TE$_{28,8}$ mode to ensure a satisfactory performance of the quasi-optical output coupler used for the transformation of the TE mode into a Gaussian-like beam and to have nearly the same electron beam radius for efficient cavity-mode excitation.

The selection process of the candidate modes with these two criteria is illustrated in Figure 2. Both the cut-off frequency and the caustic radius of a TE$_{m,n}$ mode are only dependent on the azimuthal mode number m and the radial mode number n if the radius of the cylindrical waveguide is known.

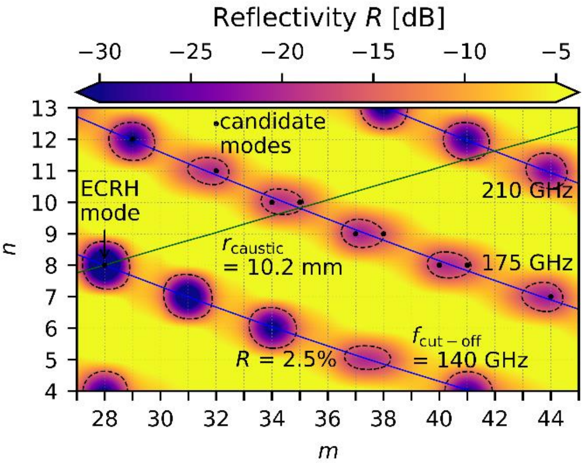


Figure 2: Selection of candidate TE modes

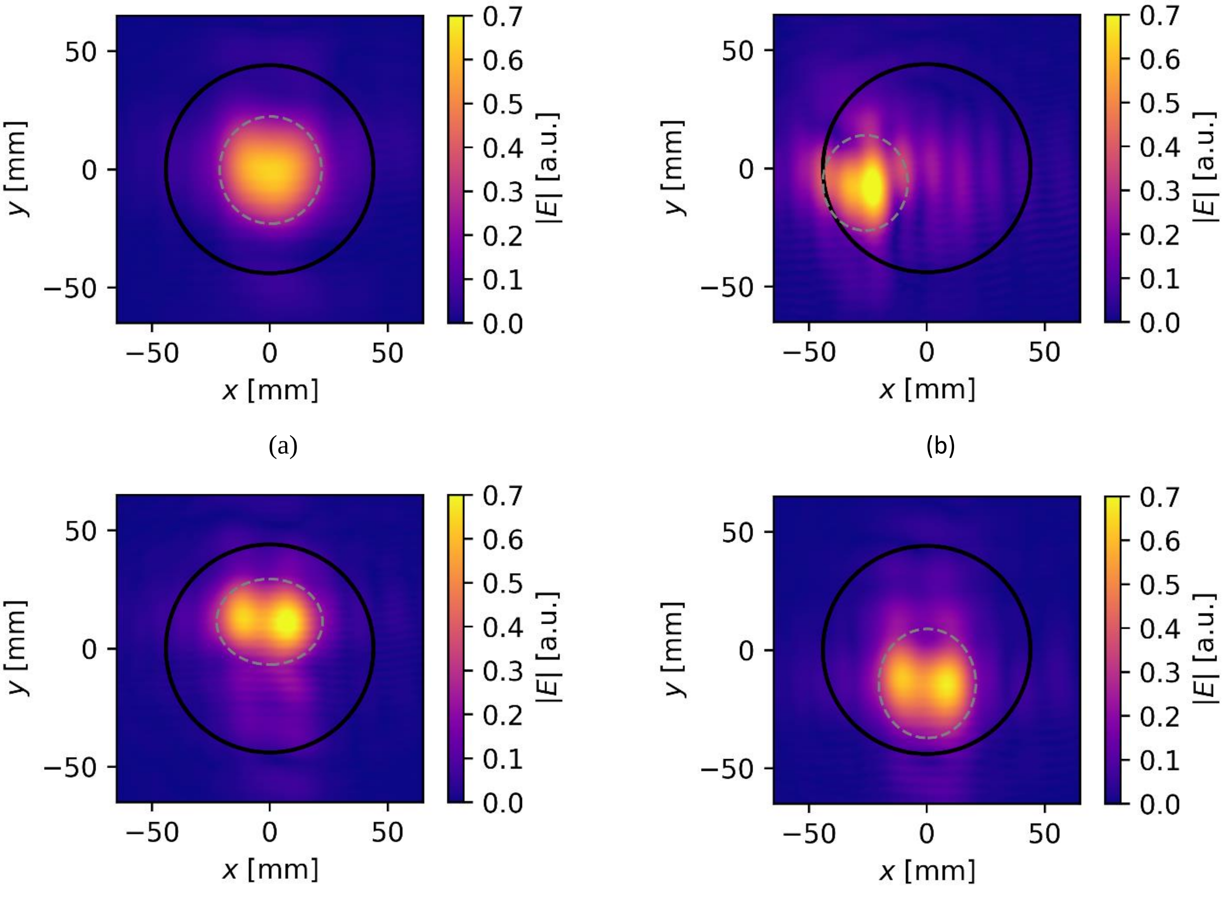
In Figure 2, m is represented on the horizontal axis and n on the vertical axis. The reflectivity at the W7-X gyrotron window, which is calculated with the cut-off frequency of the TE$_{m,n}$ mode, is color-coded – the darker the color, the lower the reflectivity. The blue lines represent the cut-off frequency, while the green line represents the caustic radius of the nominal TE$_{28,8}$ mode. The values for the reflectivity, cut-off frequency and caustic radius in Figure 2 only physically make sense for integer values of m and n. All other values are interpolated from the values obtained by integer values of m and n to help visualize the selection process. Favorable candidate modes are those in Figure 2 which have a low reflectivity and which are located close to the line of the caustic radius of the TE$_{28,8}$ mode. TE$_{m,n}$ modes with a reflectivity lower than 2.5 % are located inside the black dashed circles.

Initially, nine candidate modes are selected: the TE$_{29,12}$, TE$_{32,11}$, TE$_{34,10}$, TE$_{35,10}$, TE$_{37,9}$, TE$_{38,9}$, TE$_{40,8}$, TE$_{41,8}$ and TE$_{44,7}$ modes. These candidate modes are analyzed in the quasi-optical system of the W7-X gyrotron[11] to determine their resulting output beam at the window of the gyrotron. The simulations are performed by using the in-house developed code *KarLESS*[12]. For comparison, the operation of the quasi-optical system at the nominal TE$_{28,8}$ mode at the 140 GHz operation was also simulated. In Figure 3, the electric field at the window of the gyrotron is presented for the operation at the nominal TE$_{28,8}$ mode at 140 GHz and three modes (TE$_{29,12}$, TE$_{34,10}$ and TE$_{35,10}$) operated at 175 GHz. The black circles represent the border of the window, while the grey dashed line represents the waist of the optimal fitted Gaussian beam. For the TE$_{28,8}$ mode, the resulting RF beam passes through the center of the window and its electric field looks very close to the ideal Gaussian beam. The Gaussian mode content of the TE$_{28,8}$ mode approaches 97 %.

From the electric field of the three candidate modes operating at 175 GHz at the window, two observations can be made:

- The output beam at the window does not look like an almost perfect Gaussian beam, as it is the case for the TE$_{28,8}$ mode. Thus, their Gaussian mode content is expected to be lower than that of the TE$_{28,8}$ mode.
- The center of the output beam on the window is shifted from the center of the window. This is critical in the case of some candidate modes, for which a part of the output beam hits the rim of the window. This is not acceptable since it could cause a serious damage on the window.

The modes for which part of the output beam hits the window rim are discarded from the candidate list. The cut-off frequency $f_{\text{cut-off}}$, reflectivity R at the window, Gaussian mode content (G.M.C.), radial deviation Δr from the center of the window and stray radiation η_{stray} from the quasi-optical system inside the gyrotron of the remaining candidate modes are shown in Table I. The parameters of the TE$_{28,8}$ mode are also shown as a reference.



(a) (b) (c) (d)

Figure 3: Electric field at the window for the $TE_{28,8}$ (a), $TE_{29,12}$ (b), $TE_{34,10}$ (c) and $TE_{35,10}$ (d) modes

Table I: Remaining candidate modes after the investigation of the window and quasi-optical system

Mode	$f_{\text{cut-off}}$ [GHz]	R [%]	G.M.C. [%]	Δr [mm]	η_{stray} [%]
$TE_{28,8}$	140.02	0.002	97.21	0.5	2.89
$TE_{32,11}$	176.08	0.961	76.30	10.8	5.78
$TE_{34,10}$	173.72	1.176	86.96	11.3	2.33
$TE_{35,10}$	176.59	1.996	87.65	14.2	4.41
$TE_{37,9}$	173.78	0.802	83.99	11.4	2.92
$TE_{38,9}$	176.76	2.419	83.46	13.4	5.47

III. Electron Gun

The design of the MIG in the W7-X gyrotron is optimized to generate an electron beam appropriate for an efficient interaction in the cavity with the nominal $TE_{28,8}$ mode (10.15 mm guiding center radius).[5] For each candidate mode determined in the previous section, the possibility of the existing MIG design to generate an electron beam with reasonable electron beam parameters in the cavity was investigated. The electron gun was simulated by using the electron optics code *Ariadne*.[13] The simulations were done considering a short-pulse (SP) operation (non-neutralized beam) and long-pulse (LP) operation (neutralized beam). The neutralization in LP operation was considered to be 60 % for the W7-X gyrotron[14,15].

The required magnetic field for operation at 175 GHz is in the range of 7 T. Because the existing magnet cannot produce such high magnetic field, it is considered that the gyrotron will be installed in a new magnet.

The exact value of the magnetic field for the operation of the gyrotron at 175 GHz depends on several other parameters such as the accelerating voltage V_{acc} or the beam voltage V_{b} and the beam current I_{b}. Considering the required output power (500 kW) and a conservative expectation for the electronic efficiency (25 %) in the cavity and for the mm-wave losses (20%) in the gyrotron, a first preliminary estimation for V_{acc}, V_{b} and I_{b} as a function of B_{c} can be achieved as shown in Fig 4. Similar to[16], several operating points (OP) based on the choice of B_{c} are defined.

The operating points represent a first estimation of the operating parameters of the gyrotron based on simple analytical equations. The more precise operating parameters are determined with cavity interaction simulations, as shown in the next section.

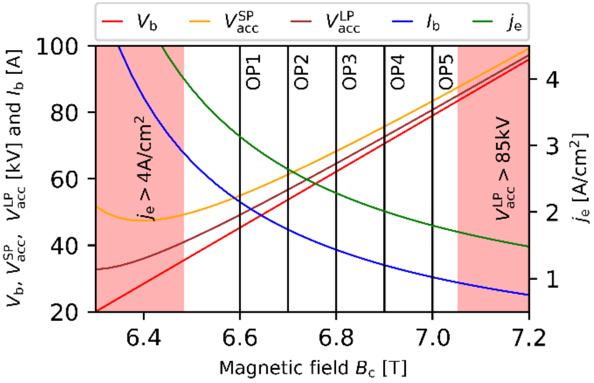


Figure 4:Definition of operating points. An output power P_{out} of 500 kW with internal and external losses in the range of 20 %, an electronic efficiency of 25% and a pitch factor α of 1.2 are assumed.

Five different OPs are defined as it is shown in Figure 4 and their operating parameters are listed in Table II.

The electron gun is simulated by using *Ariadne* to determine the parameters of the electron beam at the middle of the cavity for all OPs. In the simulations, a magnetic system with three degrees of freedom is considered for the generation of the required magnetic field. Therefore, it is possible to define a large variety of magnetic profiles, setting the magnetic field B_{c} in the cavity, the magnetic compression which determines the guiding center radius r_{gc} in the cavity center, and the angle $\varphi_{\mathrm{B,e}}$ of the magnetic field at the emitter. For each OP, a simulation with a parameter sweep over r_{gc} and $\varphi_{B,\mathrm{e}}$ was performed.

An important beam parameter is the pitch factor α (velocity ratio). If the pitch factor is too low, the energy transfer from the electron beam to the TE mode is low and the desired TE mode could not be excited. On the other hand, a too high pitch factor results in adiabatically reflected electrons, which could influence the gyrotron operation.[17,18] Thus, for each candidate mode a reasonable value for α should be achieved. Typical values are between 1.2 and 1.4.

Table II: Operating points

OP	B_{c} **[T]**	$V_{\mathrm{acc}}^{\mathrm{SP}}$ **[kV]**	$V_{\mathrm{acc}}^{\mathrm{LP}}$ **[kV]**	V_{b} **[kV]**	I_{b} **[A]**
OP1	6.6	54.93	49.14	45.28	53.00
OP2	6.7	61.26	56.73	53.71	44.68
OP3	6.8	68.28	64.59	62.14	38.62
OP4	6.9	75.69	72.62	70.57	34.01
OP5	7.0	83.37	80.75	79.00	30.38

For the $\mathrm{TE}_{32,1}$ mode, as it is concluded from the simulations, the pitch factor is too high in all OPs, which makes this mode unsuitable for the operation at 175 GHz. The $\mathrm{TE}_{34,10}$ and $\mathrm{TE}_{35,10}$ modes have their highest pitch factor at OP5 with a value of 1.05 and 0.97, respectively, for SP operation and 0.98 and 0.91, respectively, for LP operation. Although the pitch factor is significant lower than the typical values, both modes could still be excited in the cavity, as it is presented in the next section. For the $\mathrm{TE}_{37,9}$ and $\mathrm{TE}_{38,9}$ modes, the highest pitch factor is reached at OP5. However, for both modes, the values are below 0.7, which is considered as extremely low for the excitation and the efficient interaction of the mode in the cavity. Thus, out of the five remaining candidate modes, the electron gun can only generate a suitable electron beam for the $\mathrm{TE}_{34,10}$ and $\mathrm{TE}_{35,10}$ modes.

IV. Cavity

The interaction between the electron beam and the most promising candidate modes in the cavity[5] has been studied by using EURIDICE[19]. First, a single-mode analysis was performed to validate the excitation of each candidate mode and to estimate the amount of generated power. In the single-mode analysis, the generated power P_{gen} is estimated as a function of the beam voltage for each candidate mode. I_{b} and B_{c} should be tuned from the estimated values defined by the OPs, to excite the modes and to achieve the required generated power in the cavity. In Table III and Table IV, the resulting operating parameters, the generated power and ohmic wall loading ρ (with an effective electric conductivity of the cavity wall of 1.73×10^7 S/m) are shown for the two remaining candidate modes. The significant deviation of the operating values in comparison with the values defined for the operating point is explained by the lower pitch factor used in the cavity simulations compared to that used for the definition of the OPs. Additional *Ariadne* simulations were performed to check the operation of the electron gun using the tuned operating parameters. It was concluded that the quality of the electron beam does not change significantly with the tuned values.

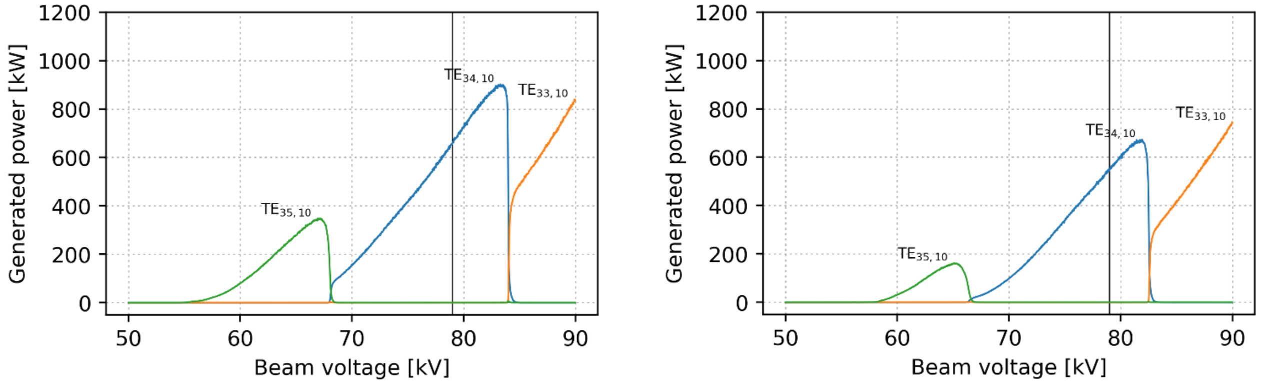
A multi-mode analysis was also performed to ensure that mode competition does not influence the operation of the higher frequency modes. In these simulations, a list of forty-two competitive TE modes, which have a frequency in the range between -5 % to +10 % of the frequency of the main mode and a coupling factor higher than 50 % of the coupling factor of the main mode, were considered. The results of the multi-mode analysis are shown in Figure 5, where only the excited TE modes are displayed. The analysis shows that the mode competition for the candidate modes is not critical. The higher pitch factor in SP operation results in a higher generated power compared to LP operation.

Table III: Operating parameters for SP operation

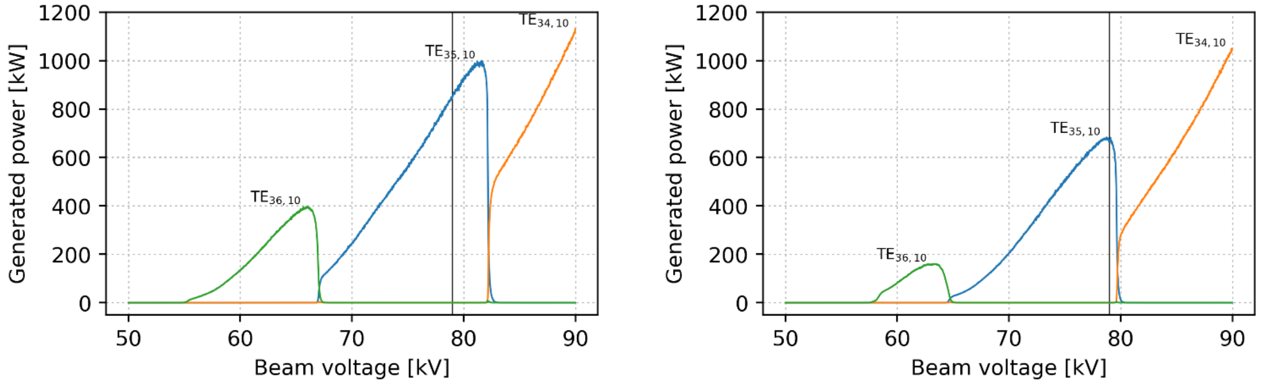
Mode	**B_c [T]**	**I_b [A]**	**V_b [kV]**	**P_{gen} [kW]**	**ρ [kW/cm^2]**
$TE_{34,10}$	6.98	40	79	659	1.34
$TE_{35,10}$	7.08	50	79	853	1.61

Table IV: Operating parameters for LP operation

Mode	**B_c [T]**	**I_b [A]**	**V_b [kV]**	**P_{gen} [kW]**	**ρ [kW/cm^2]**
$TE_{34,10}$	6.99	40	79	549	1.04
$TE_{35,10}$	7.10	50	79	670	0.98



(a) $TE_{34,10}$ in SP operation *(b) $TE_{34,10}$ in LP operation*



(c) $TE_{35,10}$ in SP operation *(d) $TE_{35,10}$ in LP operation*

Figure 5: Multi-mode analyses for the $TE_{34,10}$ in SP (a) and LP (b) operation and $TE_{35,10}$ mode in SP (c) and LP (d) operation

V. Conclusion

In this work, the possibility to operate one of the 140 GHz W7-X gyrotrons at a higher frequency for the CTS diagnostic was investigated. The operation of the tube at a higher frequency requires the compatibility with the four main gyrotron subcomponents: (i) the window, (ii) the quasi-optical output coupler, (iii) the electron gun and (iv) the cavity. Each of these subcomponents was studied separately using suitable simulation tools. Nine candidate modes, which have a cut-off frequency close to 175 GHz and caustic radius close to the one of the $\mathrm{TE}_{28,8}$ mode, have been identified. After investigating the operation of each candidate mode in the main subcomponents of the gyrotron, only two modes, the $\mathrm{TE}_{34,10}$ and $\mathrm{TE}_{35,10}$ modes, are suitable for the operation at 175 GHz. A comparison of both modes is shown in Table V.

To achieve an RF output power in the range of 450 kW for CTS, a generated power in the cavity in the range of 540 kW is required, considering internal and external RF losses in the order of 20 %. This requirement is fulfilled for both modes.

Table V: Comparison between $\mathrm{TE}_{34,10}$ and $\mathrm{TE}_{35,10}$ modes

	$\mathrm{TE}_{34,10}$		**$\mathrm{TE}_{35,10}$**	
	SP	**LP**	**SP**	**LP**
Excited frequency [GHz]	173.92	173.91	176.78	176.75
Reflectivity at the window [%]	0.83	0.84	2.48	2.42
Gaussian mode content [%]	86.96	86.96	87.65	87.65
η_{stray} [%]	2.33	2.33	4.41	4.41
Guiding center radius [mm]	9.80	9.80	9.90	9.90
P_{gen} [kW]	659	549	853	670
I_{b} [A]	40	40	50	50
V_{b} [kV]	79	79	79	79
B_{c} [T]	6.98	6.99	7.08	7.10

Both modes have a similar Gaussian mode content of 87 %. The reflection at the window as well as the stray radiation from the quasi-optical system inside the gyrotron are much lower for the $\mathrm{TE}_{34,10}$ than for the $\mathrm{TE}_{35,10}$ mode, which makes the $\mathrm{TE}_{34,10}$ mode more suitable for the operation at 175 GHz. Furthermore, the electron gun produces an electron beam with a higher pitch factor for the $\mathrm{TE}_{34,10}$ mode than for the $\mathrm{TE}_{35,10}$ mode. Therefore, less beam current is needed to excite the $\mathrm{TE}_{34,10}$ mode in the cavity. This allows to operate the gyrotron at similar values for beam current than the ones used for the nominal operation at 140 GHz. On the other hand, the operation at 175 GHz with the $\mathrm{TE}_{35,10}$ mode requires a much higher beam current to excite the mode in the cavity.

As it is theoretically shown by the simulations, it is possible to operate the 140 GHz W7-X gyrotron at the frequency of 175 GHz and based on several criteria the most suitable operating mode for this is the $\mathrm{TE}_{34,10}$ mode.

Since the existing magnet of the gyrotron cannot provide the required magnetic field for the operation at 175 GHz, a new 7 T magnet will be ordered. The new magnet shall allow the operation of the W7-X gyrotron both at 140 GHz and at 175 GHz.

The broadband quasi-optical transmission line,[20] used for the transmission of the mm-wave beams of ECRH gyrotrons towards the W7-X torus, will also be used for the transmission of the CTS probing beam at the higher frequency.[4] Mode converting phase correcting mirrors with non-quadratic surface contour function,[21,22] which are placed in the matching optics unit after the gyrotron output window, can further improve the quality of the mm-wave output beam at 175 GHz.

Experimental testing of one of the W7-X gyrotrons at 175 GHz with the new magnet is scheduled for 2021.

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Data Availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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