

## MODE SELECTION FOR A 170 GHz, 1 MW GYROTRON\*

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The European development of a gyrotron for ITER is focused on a 170 GHz, 2 MW CW coaxial-cavity gyrotron [1], [2]. However, a design of a 170 GHz, 1 MW CW gyrotron, employing a conventional hollow-waveguide interaction cavity, has also been initiated as a fallback solution in case the ambitious coaxial concept fails to demonstrate the anticipated performance in time [2]. To design a gyrotron, a set of suitable candidate operating TE modes must be specified first. We have come up with such a group of  $TE_{mp}$  modes for the aforementioned 170 GHz, 1 MW CW conventional gyrotron. This pool of modes is presented, together with simulation results for the most promising operating mode so far.

In order to have 1 MW of available power at the gyrotron window, 1.15 MW of generated RF power should be targeted to account for a typical 15 % loss in the tube. For CW operation at this output power, the realistic peak ohmic loading of the walls should not exceed 2 kW/cm<sup>2</sup>. Other physical and technological constraints related to the electron gun, the interaction cavity and to voltage depression should also be obeyed [3], [4]. These are listed in Table I. Moreover, since the 170 GHz, 1 MW conventional gyrotron is designed as a fallback solution, we have taken into account two additional constraints in order to keep the new design close to the successful 140 GHz, 1 MW CW gyrotron for W7-X [5], existing at FZK, in order to benefit from the gained experience. We thus confined the electron beam radius  $R_b$  as  $9.18 \text{ mm} < R_b < 11.22 \text{ mm}$  ( $\pm 10\%$  of the beam radius in the 140 GHz gyrotron) and the ratio of the caustic radius  $R_c$  of the operating mode to the outer wall radius  $R_o$  as  $0.45 < R_c/R_o = m/\chi_{mp} < 0.55$  (to also facilitate the design of the launcher). Finally, to avoid severe mode competition, we searched for modes with eigenvalue  $\chi_{mp} < 75$ . (Note that the eigenvalue of the operating mode in both of the conventional 170 GHz, 1 MW gyrotrons for ITER presented in [6], is below 64.) Taking into account all the constraints above, choosing a realistic value  $\alpha = 1.3$  for the electron velocity ratio and a typical value  $\theta_c = 22^\circ$  for the angle

**Table I:** Physical and technological constraints

1. Voltage depression:	$\Delta V \leq 10 \%$
2. Limiting current over beam current:	$I_l/I_b \geq 2$
3. Guiding-centre spread:	$\Delta_{gc} \leq 0.25(\lambda/2)$
4. Emitter radius:	$R_{em} \leq 60 \text{ mm}$
5. Magnetic compression:	$b_c \leq 40$
6. Electric field at the emitter surface:	$E_c \leq 7 \text{ kV/mm}$
7. Anode-cathode distance:	$d_{ac} > 2r_{Lc}$
8. Emitter current density:	$J_{em} \leq 4 \text{ A/cm}^2$
9. Space-charge-limited current density:	$J_{em}/J_{sc} \leq 0.25$
10. Diffractive quality factor:	$Q_{dif} > Q_{dif,min} = 4\pi(L_G/\lambda)^2$
11. Percentage of ohmic losses:	$P_{ohm}/P_{out} \leq 4 \%$
12. Fresnel parameter:	$C_F \geq 0.9$

of the emitter tilted surface, and targeting to 1.3 MW of generated RF power (to incorporate a safety margin in the design), we came up with the 18 candidate operating modes listed in Table II. This was done using a systematic procedure [7] based on the normalised variables approach and assuming Gaussian field profiles with characteristic length  $L_G$ . The maximum achievable transverse efficiency  $\eta_{\perp} \cong \eta_{el}(\alpha^2 + 1)/\alpha^2$ , where  $\eta_{el} = (P_{out} + P_{ohm})/(V_b I_b)$  is the interaction efficiency, was determined for each mode and is shown in the sixth column. To come down to a short-list of suitable operating modes, we used mode competition criteria. It is known that if the mode  $TE_{mp}$  is the operating mode in a conventional gyrotron cavity, the most dangerous competing modes are the modes  $TE_{(m-3),(p+1)}$  and  $TE_{(m-1),p}$ . The first one may prevent the excitation of the  $TE_{mp}$  mode, whereas the second may reduce the voltage range of stable operation of the  $TE_{mp}$  mode. For that reason, in Table II, the frequency separations  $\Delta f1 = [\chi_{mp} - \chi_{(m-3),(p+1)}]/\chi_{mp} \times 100 \%$  and  $\Delta f2 = [\chi_{mp} - \chi_{(m-1),p}]/\chi_{mp} \times 100 \%$  are also shown. Demanding high  $\Delta f1$ , we arrived at the short-list of the five modes highlighted in bold.

The  $TE_{34,10}$  mode was considered first, since it is the mode with the highest eigenvalue and thus capable of more output power. Several cavity designs were tested performing time-dependent, multi-mode simulations of the start-up of the tube and the operating point. In all cases of interest, the code *COAXIAL*, existing at HUT, predicted stable single-mode operation at the nominal values. However, this was not the case with the code-package *CAVITY*, existing at FZK, according to which the mode was not capable of stable oscillations above 1 MW. This discrepancy between the codes is under investigation. It is understood that under these circumstances, the  $TE_{34,10}$  mode could not be regarded as a safe choice. The  $TE_{32,9}$  mode was then chosen as an alternative solution because it has the lowest eigenvalue and may thus be more competent in terms of mode competition and stability.

**Table II:** Candidate operating modes (final short-list in bold)

TE mode		$\chi_{mp}$	$R_b$ (mm)	$R_c/R_o$	% Transverse efficiency $\eta_{\perp}$	% Freq. sep. TE $_{(m-3),(p+1)}$	% Freq. sep. TE $_{(m-1),p}$
$m$	$p$						
32	8	64.982	9.420	0.492	61	0.180	1.870
<b>32</b>	<b>9</b>	<b>68.563</b>	<b>9.420</b>	<b>0.467</b>	<b>66</b>	<b>0.301</b>	<b>1.792</b>
33	8	66.194	9.708	0.499	62	0.139	1.830
<b>33</b>	<b>9</b>	<b>69.789</b>	<b>9.708</b>	<b>0.473</b>	<b>66</b>	<b>0.262</b>	<b>1.756</b>
<b>33</b>	<b>10</b>	<b>73.330</b>	<b>9.708</b>	<b>0.450</b>	<b>70</b>	<b>0.356</b>	<b>1.688</b>
34	8	67.403	9.996	0.504	63	0.101	1.793
<b>34</b>	<b>9</b>	<b>71.011</b>	<b>9.996</b>	<b>0.479</b>	<b>67</b>	<b>0.226</b>	<b>1.721</b>
<b>34</b>	<b>10</b>	<b>74.565</b>	<b>9.996</b>	<b>0.456</b>	<b>70</b>	<b>0.321</b>	<b>1.656</b>
35	7	64.917	10.284	0.539	55	-0.101	1.834
35	8	68.608	10.284	0.510	65	0.065	1.757
35	9	72.230	10.284	0.485	69	0.191	1.688
36	7	66.105	10.572	0.545	58	-0.135	1.797
36	8	69.811	10.572	0.516	66	0.031	1.723
36	9	73.446	10.572	0.490	69	0.157	1.656
37	7	67.290	10.859	0.550	58	-0.168	1.761
37	8	71.010	10.859	0.521	66	-0.001	1.689
37	9	74.659	10.859	0.496	70	0.126	1.625
38	8	72.207	11.147	0.526	66	-0.031	1.658

**Table III:** Operating parameters and calculated performance for the TE $_{32,9}$  mode

Operating Parameters		Calculated Performance	
Magnetic field $B_0$	6.76 T	Output power at RF window	1.0 MW
Beam voltage $V_b$	79.0 kV	Operating frequency	170.04 GHz
Beam current $I_b$	40.0 A	Overall efficiency w/o depr. collector	31.6 %
Beam radius $R_b$	9.5 mm	Peak ohmic wall loading	2.2 kW/cm $^2$
Electron velocity ratio $\alpha$	1.3		

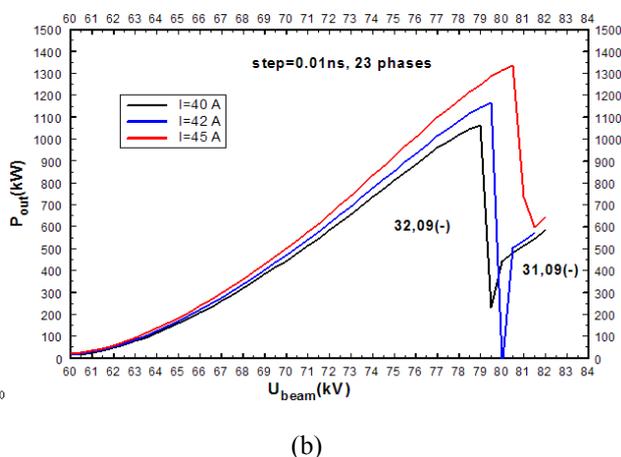
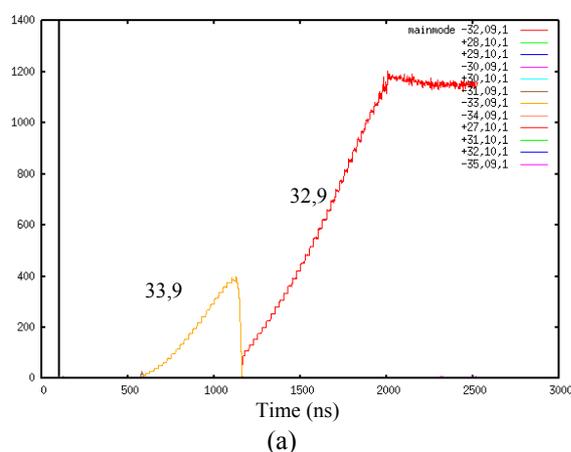


Figure 1: Start-up simulations for the operating parameters of Table III. (a) Simulation with the FZK code. Beam voltage rises during the first 2000 ns to 79 kV and then remains constant to check the stability of the operating TE $_{32,9}$  mode at the operating point. (b) Simulation with the HUT code. Apart from the nominal case with beam current  $I_b = 40$  A, the cases  $I_b = 42$  A and  $I_b = 45$  A are also shown.

Indeed, this time both the FZK and HUT codes predicted stable operation of the TE<sub>32,9</sub> mode at the nominal values. For the most successful cavity design so far, the performance as calculated by the FZK code is shown in Table III. Multi-mode simulation results from both codes are shown in Fig. 1. The TE<sub>32,9</sub> mode is also capable of 1.3 MW at  $I_b = 45$  A (safety margin). The ohmic wall loading at nominal values is somewhat high (2.2 kW/cm<sup>2</sup>, as a consequence of the low eigenvalue) but it may still be considered acceptable. Optimisation of the design for this mode together with further investigation on the TE<sub>34,10</sub> mode (and possibly on the other three modes of the short-list) are planned for the near future.

## References

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