Mode Competition Control using Triode-Type Start-up Scenario for a 236 GHz Gyrotron for DEMO

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***Abstract*— After ITER, the first real prototype of a fusion power plant is foreseen. It is named Demonstration Power Plant (DEMO). Within the EUROfusion work package "Heating and Current Drive", the conceptual designs of both a hollow-cavity and coaxial-cavity gyrotron for DEMO has been suggested. For DEMO, the major target is to achieve an output power per tube which is significantly larger than 1 MW CW at an operating frequency of up to 240 GHz. In the case of the hollow-cavity gyrotron design, a very high-order TE mode (eigenvalue > 103 at a cut-off frequency of 236 GHz) is the prerequisite for the targeted high output power. At this eigenvalue range, the excitation of the desired operating mode during gyrotron start-up becomes challenging due to a large number of competing modes. In this work, it is demonstrated by numerical simulation that mode excitation and mode competition control can be significantly facilitated by using special start-up scenarios, based on a triode electron gun.**

Keywords*— *Nuclear fusion; DEMO; electron cyclotron resonance heating; ECRH; plasma heating; gyrotron; high order modes; mode competition control; triode-type start-up.

I. Introduction

Gyrotrons are fast-wave, Vacuum Electron Devices (VEDs), which generate high power (from a few watts to several megawatts) electromagnetic waves in the sub-THz frequency range [1]. Hence, high-power (~ 1 MW), high-frequency (100 GHz – 300 GHz) gyrotrons are the only RF sources today which are capable to be used as microwave sources in thermonuclear fusion plasma experiments and future power plants for electron cyclotron resonance heating (ECRH), non-inductive current drive (CD), Collective Thomson Scattering (CTS) and plasma stability control. As an example, in total ten 140 GHz, 1 MW Continuous Wave (CW) gyrotrons are successfully installed and operating at the Wendelstein 7-X (W7-X) stellarator in Greifswald, Germany [2]. For the ITER tokamak in Cadarache (France), twenty-four 170 GHz, 1 MW CW gyrotrons are planned for a total ECRH&CD power requirement of 20 MW [3-4]. After ITER, the first prototype of a fusion power plant is foreseen, termed as DEMOnstration power plant (DEMO), which is notably intended to generate net electrical power on the grid. In addition to the net energy generation, the main aim of DEMO is to prove tritium self-sufficiency and adequate reliability. According to the European Union (EU) 2012 baseline of DEMO. the design targets and today's technical constraints of DEMO gyrotrons are listed in Table I [5]. The EU baseline has been updated to the 2015 EU DEMO1 Baseline (aspect ratio 3.1) with suggested gyrotron operating frequency close to 200 GHz [6]. Nevertheless, it is expected that the future Power Plant (FPP) will require operating frequencies up to 240 GHz.

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The minimum required output power for the hollow-cavity design is set above 1 MW, which shall be further extended to 2 MW. Systematic design studies of the hollow-cavity and coaxial-cavity DEMO gyrotrons have been presented in [7-8] and [9-10], respectively. For the hollow-cavity design, the results suggest stable excitation of the $TE_{-43,15}$ mode (eigenvalue ~ 103) with an output power of 920 kW. 2 MW output power may be achieved with a coaxial cavity design using the operating mode $TE_{-49,29}$ (eigenvalue ~ 158). In this work, the negative sign of mode indices represents the co-rotating mode and the mode eigenvalue is the root of the derivative of the Bessel function. The possibilities of fast frequency step-tunability in 2 – 3 GHz steps have been numerically demonstrated in [11]. The proposed gyrotron designs also support multi-frequency operation at 170 GHz, 203 GHz and 236 GHz [12-13]. In addition to the design goals, the present technical constraints have been considered for the realistic designs of the DEMO gyrotrons (refer Table I). It should also be noted that at KIT, the installation of an advanced gyrotron test facility is ongoing [14].

TABLE I. Design targets and technological constraints for DEMO gyrotrons [7-8].

Design targets	
Main frequency	240 GHz
Output power	> 1 MW (target: 2 MW)
Overall efficiency (with multi-stage depressed collector)	> 60%
Frequency step for fast tunability	2 – 3 GHz
Frequency step for (slow) multi-frequency operation	30 – 40 GHz
Technological constraints in the design	
Peak ohmic wall loading at cavity	≤ 2 kW/cm^2
Emitter current density	≤ 4 A/cm^2
Electric field at emitter (cathode)	≤ 7 kV/mm

TABLE II. SELECTED HIGH-ORDER MODES CONSIDERED FOR THE ANALYSIS. ALL THE SELECTED MODES HAVE NEARLY THE SAME RELATIVE CAUSTIC RADIUS ($R_{CAUSTIC}$ / R_{CAVITY}) OF 0.41-0.42 [15].

Mode name	**DM0**	DM1	DM2	DM3	DM4	**DM5**	DM6	DM7	DM8	**DM9**
Mode	**$TE_{-43,15}$**	$TE_{-44,15}$	$TE_{-45,16}$	$TE_{-48,17}$	$TE_{-50,17}$	**$TE_{-52,18}$**	$TE_{-53,19}$	$TE_{-56,20}$	$TE_{-58,20}$	**$TE_{-59,21}$**
Eigenvalue ($\chi_{m,n}$)	**103.21**	104.46	109.17	116.4	118.91	**124.87**	129.58	136.8	139.32	**144.02**
Cavity radius (mm)	**20.88**	21.14	22.09	23.55	24.06	**25.26**	26.22	27.68	28.19	**29.14**
Beam radius (mm)	**9.06**	9.28	9.49	10.10	10.51	**10.93**	11.13	11.75	12.16	**12.37**
Rel.caustic radius	**0.41**	0.42	0.41	0.41	0.42	**0.42**	0.41	0.41	0.42	**0.41**
Diffractive Q	**1443**	1445	1457	1483	1493	**1573**	1533	1553	1559	**1567**

For gyrotron operation at ~240 GHz and at power above 1 MW, a high-order operating mode (eigenvalue > 103) is mandatory, which allows a large cavity radius and a high-power handling capability. However, the mode spectrum density increases with mode eigenvalue and it might not be possible to successfully excite the desired operating mode. For the operating frequency of 236 GHz, nine operating modes having eigenvalue between 105 to 145 have been selected (See Table II) and the influence of mode eigenvalue on mode stability has been systematically studied in [15]. The results suggest an eigenvalue limit of 125 ($TE_{-52,18}$) for stable gyrotron operation with start-up condition offered by diode gun.

The performance of a gyrotron operating in a very high order mode is greatly dependent on the temporal evolution of electron beam parameters. In this paper, it is numerically demonstrated that the limitations related to the diode start-up [15] can be relaxed if a triode electron gun is used. In Section II, the effectiveness of the triode-type start-up scenario is investigated along with the possibilities of mode selectivity. The in-house code package "EURIDICE" [16] has been used for the multi-mode interaction simulations and starting current calculations.

II. TRIODE-TYPE START-UP SCENARIO

The gyrotron gun designs are classified into two types (a) diode-type gun and (b) triode-type gun. The simple schematic of the diode-type and triode-type gun are presented in Figure 1. In the case of a diode-type gun, the beam energy as well as the electron velocity ratio (pitch factor) increase with cathode voltage. It is not possible to control the beam energy and velocity ratio independently.

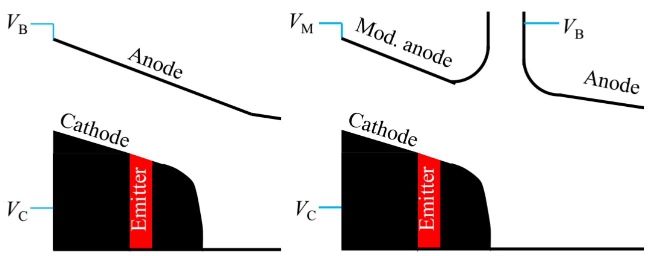


Fig. 1. Simple schematic of (a) diode-type and (b) triode-type gun. Here, V_C is the cathode voltage, V_B is the anode voltage and V_M is the modulating anode voltage.

In the case of a triode-type gun, using the modulating anode voltage, the beam energy and the velocity ratio can be controlled independently. This allows various start-up scenarios to reach the nominal values of electron beam parameters. The detailed analysis of a triode-type start-up scenario has been discussed in [17-18] and experimental verification is presented in [19-20]. At specific beam energy, the corresponding value of modulating anode voltage to have a specific velocity ratio can be calculated using [17],

$$V_M = \frac{m_e c^2}{e} \frac{\ln(1+D_F k)}{\ln(1+2k)} \left\{ \left[1 + \frac{4}{k^2} \left(\frac{1+k}{1+2k} \right)^2 \left(\frac{\gamma^2 - 1}{R_c^2 (cos\varphi_c)^2} \right) \left(\frac{\alpha_0^2}{\alpha_0^2 + 1} \right) \right]^{0.5} - 1 \right\}$$

where, $k = 1/\sqrt{R_g^2 - 1}$, $R_C = r_{ct}/r_L$, $R_g = r_{beam}/r_L$, $D_F = (cos\varphi_c \cdot d_{ac})/(k \cdot r_{ct})$. Here, d_{ac} is the cathode-anode separation distance, r_{ct} is the average cathode radius, γ is the relativistic factor and φ_c is the cathode slant angle.

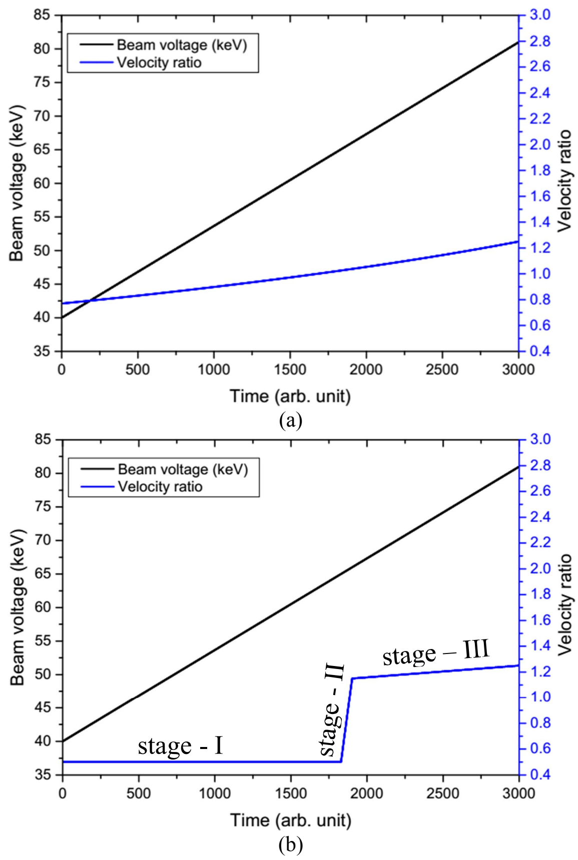


Fig. 2. Variation of the beam parameters in (a) diode start-up and (b) triode-start-up scenario.

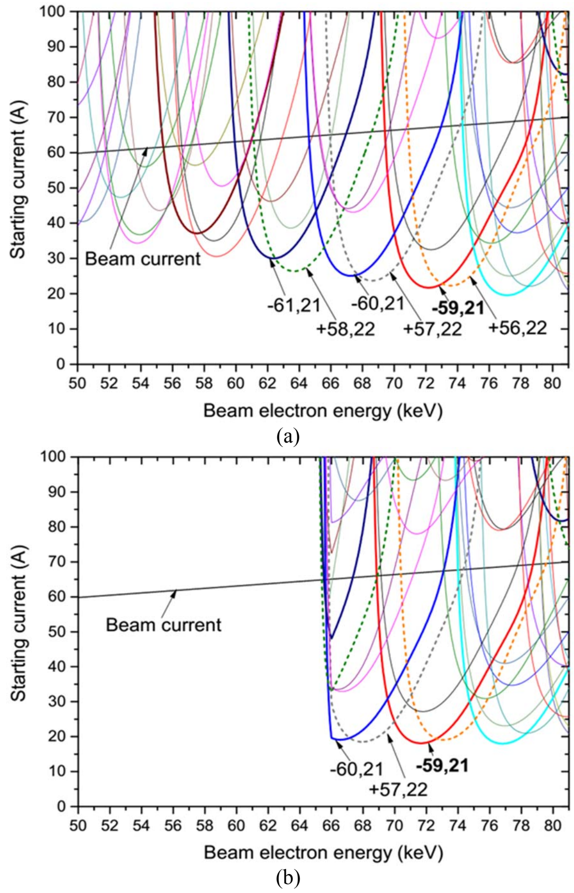


Fig. 3. Starting current plots of the relevant neighboring modes with (a) diode-type and (b) triode-type start-up scenario. During the first part of the triode start-up (stage – I), where the beam energy is less than 65 keV, the values of the mode starting current are very high because of the low-velocity ratio.

The variation of the beam parameters during diode-type and triode-type start-up scenario is compared in Figure 2. The operating mode $TE_{-59,21}$ (case DM9 of table II, eigenvalue ~ 144) is selected for this analysis to investigate the effects of the triode-type start-up scenario on mode competition. The selected operating parameters are: magnetic field B = 9.435 T, beam electron energy E = 81 keV, beam current I = 66 A, velocity ratio α = 1.25. In the diode-type start-up scenario, the beam electron energy is increased linearly from 40 keV to 81 keV, while the velocity ratio follows the adiabatic approximation. In the case of triode-type start-up, the velocity ratio changes in three stages. During stage - I, the beam energy is increased from 40 keV to 65 keV with a constant velocity ratio of 0.5. The second stage is called "transition phase" in which, the velocity ratio is increased from 0.5 to 1.15 with the beam electron energy variation of 65 keV to 66 keV. In the third stage, the velocity ratio is raised linearly up to the nominal velocity ratio of 1.25 and the beam energy is increased to the operating value of 81 keV.

The effects of the triode start-up on mode competition is shown by the comparison of the starting current plots of the diode and triode start-ups (see Figure 3). During the stage - I of the triode-type start-up, due to very low-velocity ratio, the starting currents of parasitic modes are very high, which suppresses the excitation of any parasitic mode in this stage. In the second stage of start-up, the mode having a minimum starting current value has the highest possibility of excitation (which is the $TE_{-60,21}$ mode, in Figure 3(b)).

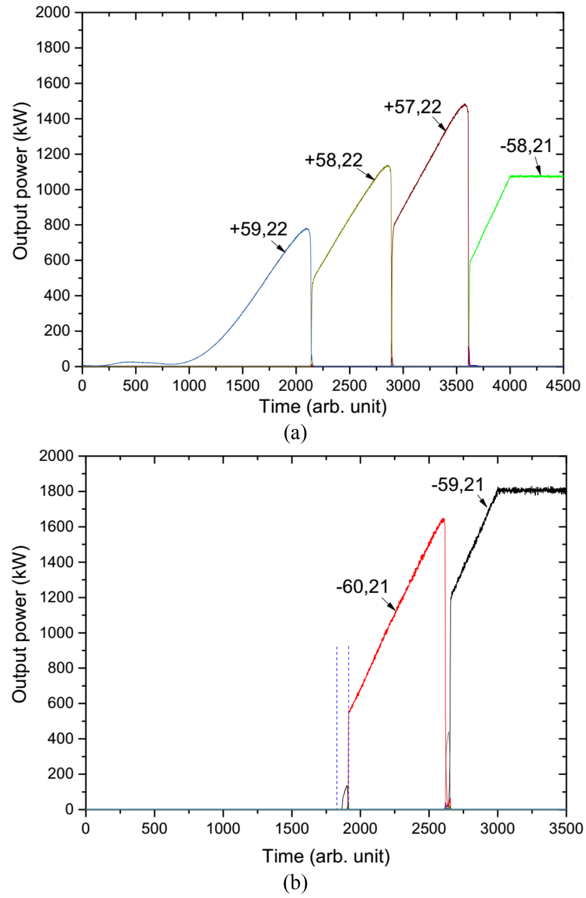
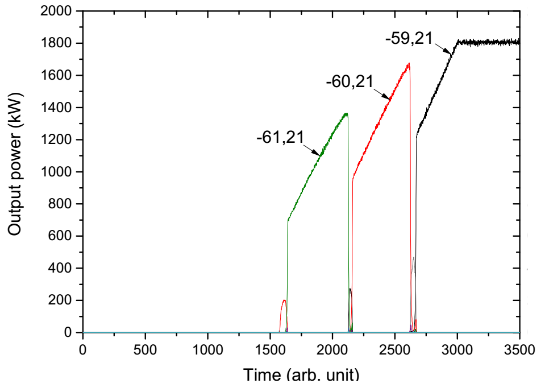


Fig. 4. Multi-mode, self-consistent simulation with operating mode $TE_{-59,21}$: (a) diode-type and (b) triode-type start-up scenario. The transition phase is indicated with dashed vertical blue lines in (b).

The results of interaction simulations with the diode-type and triode-type start-up scenario are compared in Figure 4. Realistic beam parameters (6 % rms velocity spread and λ/4 radial width) are considered for the multi-mode self-consistent simulations with 84 neighboring modes. In the case of a diode-type start-up, due to critical mode competition, it is not possible to excite the desired operating mode $TE_{-59,21}$. As discussed in [15], this result also supports the mode eigenvalue limit of 125 for diode-type start-up.

Due to the three-stage variation of the velocity ratio in the triode start-up, the excitation of parasitic modes is completely suppressed in the stage - I, which leads to the stable excitation of the desired operating mode $TE_{-59,21}$ in steady state. The reduced mode coupling during stage - I facilitates the control of mode competition.

The proper position of the transition phase and the specific variation of the velocity ratio are important for successful triode start-up. According to the position of the transition phase, the first mode excites during the start-up, which leads to the excitation of the final operating mode. After careful study of starting current plots, the position of the transition phase can be finalized for the desired start-up scenario. For example, the starting current of mode $TE_{-61,21}$ is minimum for a beam energy of 60 keV to 62 keV (see Figure 3(a)). If the transition phase is selected from 61 keV to 62 keV, the two modes $TE_{-61,21}$ and $TE_{-60,21}$ are excited before stable excitation of the operating mode $TE_{-59,21}$ (refer Figure 5(a)). Similarly, when the transition phase is selected between beam energy of 70 keV to 73 keV, the start-up condition supports the direct excitation of the operating mode $TE_{-59,21}$ (Figure 5 (b)).



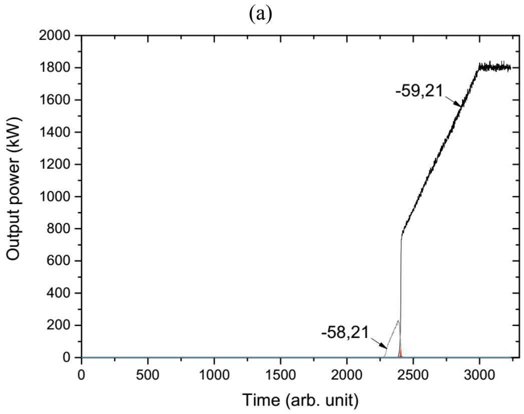


Fig. 5. Mode selectivity with triode-type start-up scenario. In (a) the pitch factor transition region is selected between 61 keV to 62 keV, while in (b) it is selected at 70 keV to 73 keV.

CONCLUSIONS

In this paper, the possibilities of the mode competition control and mode selectivity are investigated considering an advanced triode-type start-up scenario. Unlike a diode-type gun, the triode-type gun provides better control of the electron velocity ratio by selecting an appropriate modulating anode voltage. With the help of triode-type start-up, initial excitation of competing modes can be suppressed, which facilitates the stable excitation of the main operating mode. The simulation results confirm mode selectivity during the gyrotron start-up phase by the proper positioning of the transition phase between low and high pitch factor and by specific variation of the pitch factor. As compared to the diode-type start-up, the triode-type start-up supports stable gyrotron operation with even higher order modes, which will lead to higher output power.

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