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Modelling and Optimisation of a Relativistic Magnetron with Transparent Cathode with TE_{11}-mode Emission of Microwaves

David Sawert*[1,2], Pablo Vallejos[2], Frans Nyberg[2], Dragos Dancila[1,3] and Tomas Hurtig[2]
(1) FREIA, Department of Physics and Astronomy, Uppsala University, Sweden
(2) Swedish Defence Research Agency, Olof Arrhenius väg 31, 137 94 Sorunda
(3) Microwave Group, Department of Electrical Engineering, Uppsala University, Box 65, 751 03 Uppsala, Sweden

This paper presents particle-in-cell (PIC) simulations of a relativistic magnetron (RM) using a transparent cathode configuration. The RM is a device capable of generating pulsed high-power microwaves (HPM). Previous research on RMs with transparent cathode has shown favourable results regarding efficiency and oscillation rise time. In [1], Fuks et al. showed with PIC simulations an RM with a transparent cathode capable of generating HPM in the gigawatt-range with high efficiency, short rise time of oscillations, and a TE_{31}-mode. This design was experimentally tested by Leach et al. [2].

In this work, a modified diffraction output is used combined with a smaller waveguide radius in order to obtain microwaves with a clean TE_{11}-mode. We show that this design can achieve a relatively high efficiency of $\sim 37\%$ at 2.57 GHz with a peak output power of 1.1 GW, having a rise time of ~ 13 ns. The diffraction output consists of two pairs of large cavities and one pair of small cavities, as shown in Figure 1(b). Such a geometry will convert the favourable π mode (i.e. the cavity mode that is excited in the interaction region) to a TE_{11}-mode at the cylindrical waveguide [3]. Additionally, the waveguide radius is kept relatively small at $r = 7$ cm to reduce the possibility of exciting higher-order modes such as TM_{11} and TE_{01}. This is advantageous for the RM operating around a desired frequency of $2.50 - 2.58$ GHz. Parameter studies were done using PIC simulations in MAGIC3D to determine the optimal geometrical specifications for the RM. The parameters studied were the transparent cathode orientation θ ($\theta = 0^\circ$ implies that the cathodes are in direct alignment with the centres of the anode cavities), length of interaction region L_{int}, and length of emitter $L_{emitter}$. The studies concluded that optimal values are $\theta = 15^\circ$, $L_{int} = 13.5$ cm, $L_{emitter} = 4.5$ cm.

In order to understand the electron dynamics and to find the optimal beam-to-microwave efficiency η and peak output power P_{max}, we chose to study two separate magnetic field strengths ($B = 0.28$ T and $B = 0.34$ T) for various applied voltages V_{ac} over the anode-cathode (A-K) gap. The magnetic field strength B is generated by a set of Helmholtz coils placed symmetrically around the emitter, having the radius $R_{coil} = 8$ cm in order to be placed outside the RM easily. The input power P_{in} is defined as $P_{in} = V_{ac} \cdot I_c$, where I_c is the net current in the cathode while P_{max} is defined as the maximum value of the output power P_{out} (when V_{ac} has reached steady state). Since P_{out} oscillates, the beam-to-microwave efficiency is defined as $\eta = \overline{P_{out}}/P_{in}$ (where the bar symbol denotes time average). The applied voltage V_{ac} was modelled as a ramp function with a rise time of $t_{rise} = 4$ ns. In Figure 2(a), we show that there is an optimal range for the voltage V_{ac} for a given value of B where a TE_{11} mode is excited. If V_{ac} is too low, there is either no microwave excitation or excitation of a different mode but at low efficiency. This is shown in Figure 2(a), where a TE_{21} mode was excited for $B = 0.28$ T at $V_{ac} = 205$ kV and $B = 0.34$ T at $V_{ac} = 258$ kV. For higher values of V_{ac}, we cross the Bunemann-Hartree condition for a different cavity mode in the interaction region, here denoted f_2, which becomes dominant and results in the excitation of a TE_{21} mode. This is illustrated in Figure 2(a) for $B = 0.34$ T and $V_{ac} > 332$ kV.

The highest efficiency of $\eta = 37.0\%$ occurs at $V_{ac} = 318$ kV and $B = 0.34$ T, having a peak output power of $P_{max} = 960$ MW. However, the highest $P_{max} = 1.1$ GW occurs at $V_{ac} = 328$ kV and $B = 0.34$ T, with a slightly lower $\eta = 36.5\%$. For the lower value of $B = 0.28$ T, the highest efficiency of $\eta = 35.4\%$ is found when $V_{ac} = 234$ kV, resulting in $P_{max} = 410$ MW. The input power, output power, and average output power for the highest performing case are shown in Fig.2(b). After ~ 11 ns, the input power stabilises at $P_{in} = 1.55$ GW while the output power stabilises after ~ 13 ns. The frequency of the resulting TE_{11} mode is 2.57 GHz, which is well above the cutoff frequency of the π mode in the interaction region at 2.53 GHz. For the cases where the TE_{21} mode was excited for lower V_{ac}, the frequency increased to 2.73 GHz for $B = 0.28$ T and 2.61 GHz for $B = 0.34$ T. On the other hand, excitation of the TE_{21} mode for higher V_{ac} resulted in a lower frequency of 2.37 GHz for both values of B. In Figure 3, the voltage V_{ac} and impedance Z_{ac} are shown for the two best simulations for each value of B. The voltages for both cases rise to a maximum after ~ 6 ns but decrease due to a current flow between the A-K gap and hence an impedance drop. The impedance for the case of $B = 0.34$ T settles at $Z_{ac} = 69$ Ω after ~ 12 ns, while the impedance for $B = 0.28$ T is significantly higher at $Z_{ac} = 91$ Ω and settles after a longer time of ~ 16 ns.

In conclusion, we have shown that the transparent cathode configuration for an RM is a design worth investigating further. The short rise time of ~ 13 ns is favourable for RMs, as well as the relatively high efficiency of $\eta = 37\%$ and peak output power of $P_{max} = 1.1$ GW.

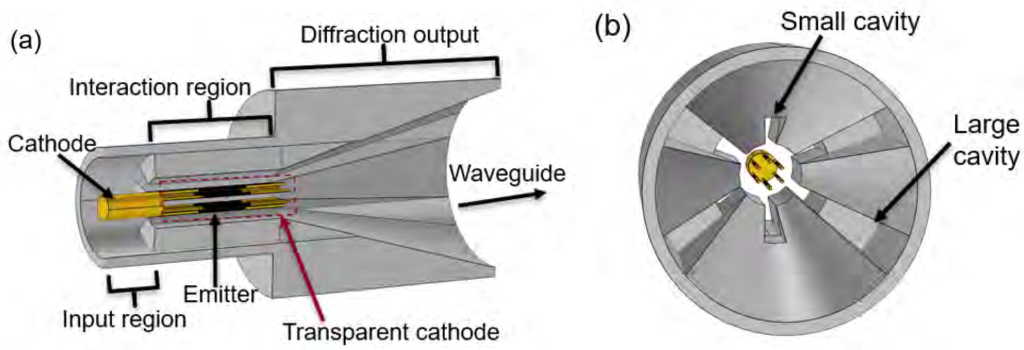

Figure 1. a) 3D cross section of the RM. b) Diffraction output viewed from the waveguide.

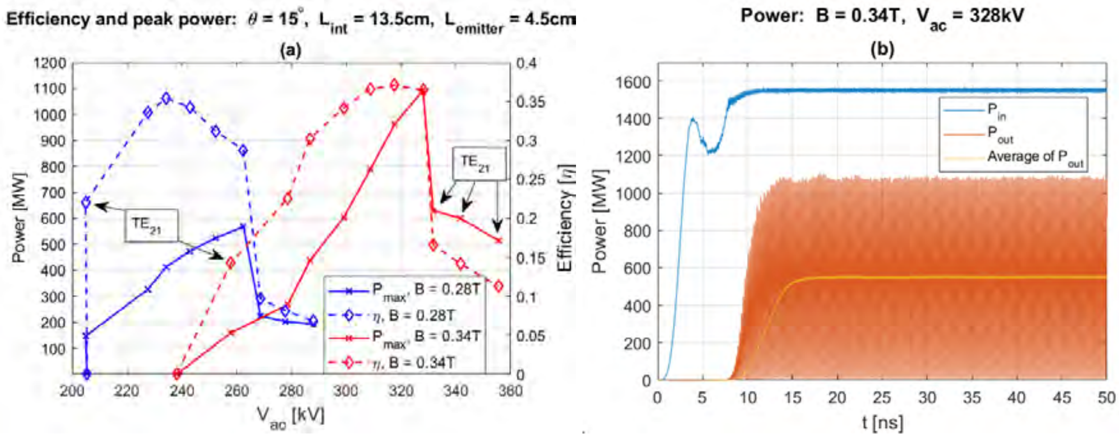

Figure 2. a) Double y-axis graph showing peak output power (left y-axis) and efficiency (right y-axis) for $B = 0.28\ T$ and $B = 0.34\ T$. b) Input, output, and average output power for the highest performing case.

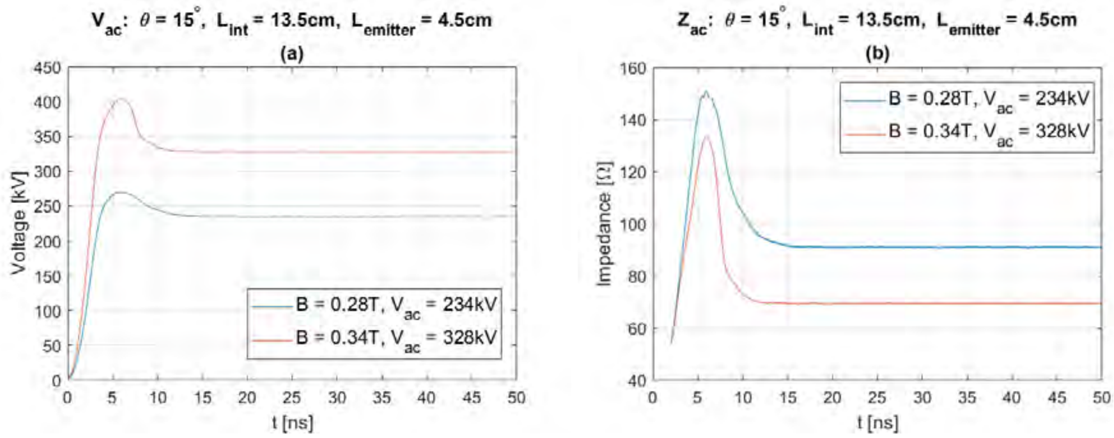

Figure 3. Voltage (a) and impedance (b) over the A-K gap for the best cases for $B = 0.28\ T$ and $B = 0.34\ T$.

References

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