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High voltage analysis of electron gun for low power and high power gyrotron

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The paper presents the high voltage analysis of Magnetron Injection Gun for 42 GHz, 200 kW and 120 GHz 1 MW gyrotrons. The Finite Element Analysis code TRAK has been used for the analysis of high voltage breakdown. In the analysis, the potential and electric field are estimated only at the critical regions between two electrodes, where the chance of voltage breakdown is prominent.

Keywords: Gyrotron, Electron gun, Electric breakdown, High voltage

1 Introduction

The gyrotron oscillator, sometimes referred to as the "electron cyclotron resonance maser" or "gyro-monotron", is a high-power high-frequency source of coherent electromagnetic radiation[1-3]. The name now refers to a class of devices including both oscillators and amplifiers. It consists of a magnetron injection gun, which generates an annular electron beam which is focused onto an open cavity resonator along an axial magnetic field, created by a superconducting magnet. In the cavity, the *RF* field interacts with the cyclotron motion of the electrons in the beam and converts the transverse kinetic energy into an *RF* beam which may then be internally converted into a Gaussian beam. The spent electron beam leaves the cavity and propagates to the collector where it is collected. In MIG, the electron beam is emitted from the conical shaped cathode working on the principle of thermionic emission, which is based on the heating of an emitting surface to allow electrons to overcome the work function and escape up to the surface. The high voltage analysis is also a cause of failure of microwave tube. The high voltage breakdown is the process of the transformation of a non-conducting material into a conductor as a result of applying to it a sufficiently strong voltage (breakdown voltage). The high voltage breakdown can occur inside (vacuum area) or outside (air) of the device at any of several locations [4]. There are some locations in gyrotron, like the MIG (between electrodes, between leads or from electrodes or leads to ground), the collector (between electrodes, between leads or from electrodes or leads to ground) and the high power *RF* structure which are critical to high voltage breakdown[4] as shown in Fig. 1.

The high voltage breakdown depends on mainly two factors. These are (i) the applied field level and local field enhancement effects and (ii) the breakdown field of the medium[4-9] (vacuum, gas, liquid or solid), To avoid these types of breakdown, it is important to see the effect of high voltages present between the different electrodes of the MIG through estimation of potential profile, electric field strength at different gun locations. Since, the beam voltages applied on the different electrodes (anodes) are greater than the voltage on the cathode. To avoid the voltage break down between two electrodes kept at different potentials, a certain minimum distance is must between these two electrodes. In the present paper, high voltage analysis of the Magnetron Injection Gun for 42 GHz, 200 kW gyrotron and 120 GHz 1 MW gyrotron has been developed in India, is presented.

2 High Voltage Analysis of MIG for 42 GHz 200 kW Gyrotron

To avoid the voltage break down between the two electrodes, it is important to estimate the potential profile and the electric field strength at the different locations of MIG. Therefore, high voltage analysis of designed MIG has been carried out in detail with the help of the software[10] TRAK, The approach followed for high voltage analysis is shown with the help of flow-chart in Fig. 2.

The designed Magnetron injection gun consists of a dispenser cathode and two anodes, namely, the modulating anode and the accelerating anode. A 2D axis-symmetric model (Fig. 3) has been created in TRAK code for minimizing the complexity of modeling and the solution time. The geometrical parameters used to model the MIG by using TRAK and the potential values applied (obtained from MIG design by using EGUN code) are given[11] in Table 1. In the analysis, the potential and electric field intensity have been estimated only at the critical regions between the two electrodes, where the chance of voltage breakdown is prominent. Thus, different

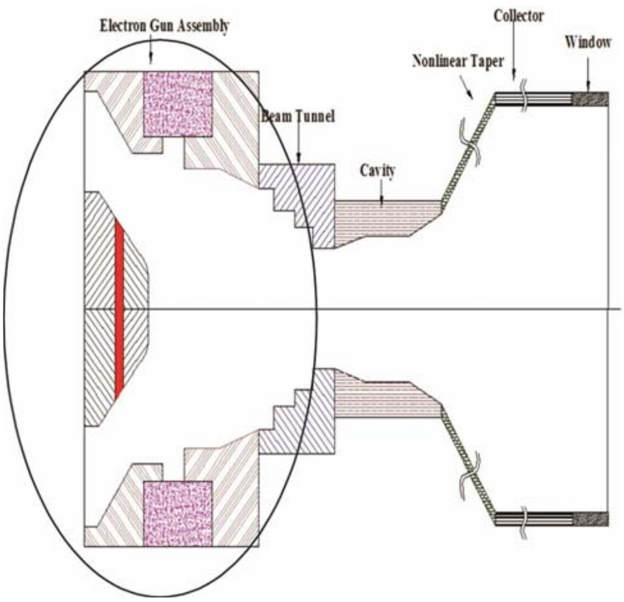

Fig. 1 — Regions in a gyrotron where electrical breakdown may occur

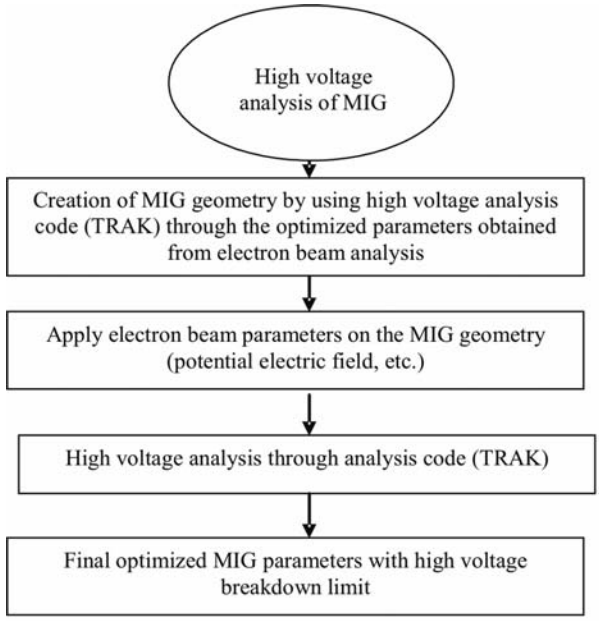

Fig. 2 — Flow chart for high voltage analysis of MIG

Table1 — Various parameters used to model the MIG by using TRAK

Cathode radius (r_c)	22.6 mm
Slant length of cathode (l_s)	6.4 mm
Modulating anode voltage (V_a)	28.5 kV
Accelerating anode voltage (V_0)	65 kV

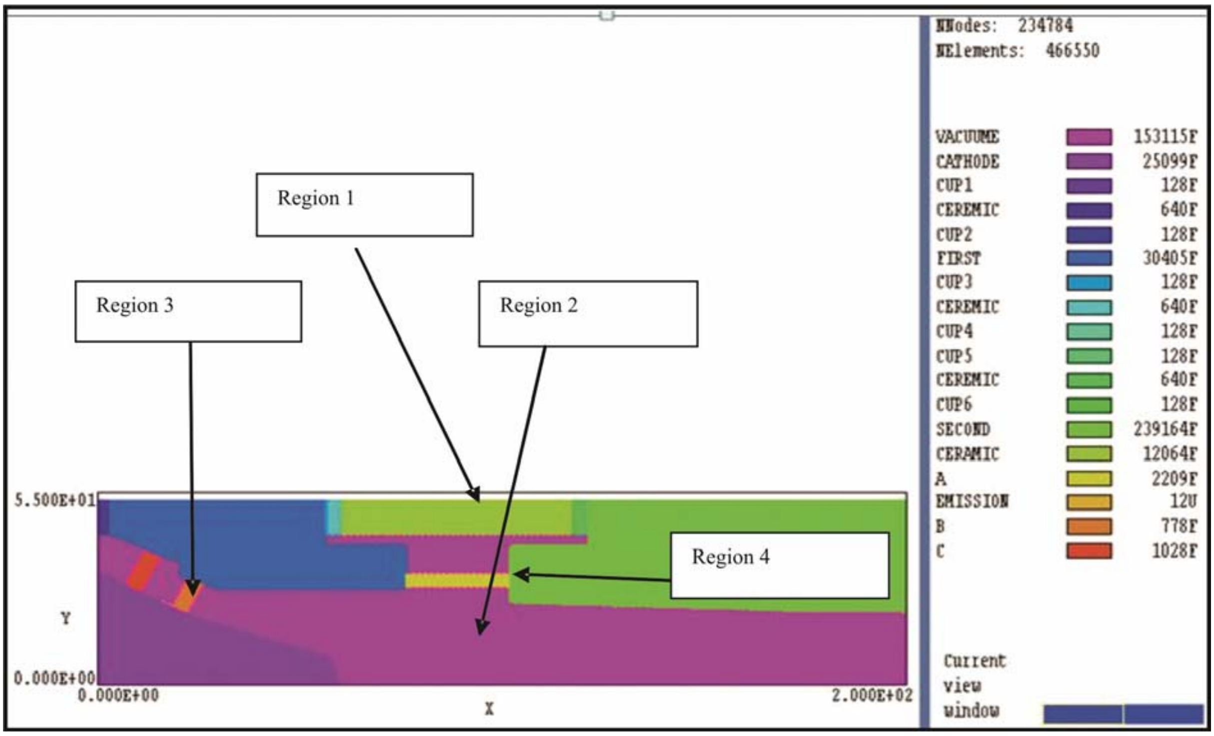

Fig. 3 — 2D axis-symmetric model of MIG modeled in TRAK code

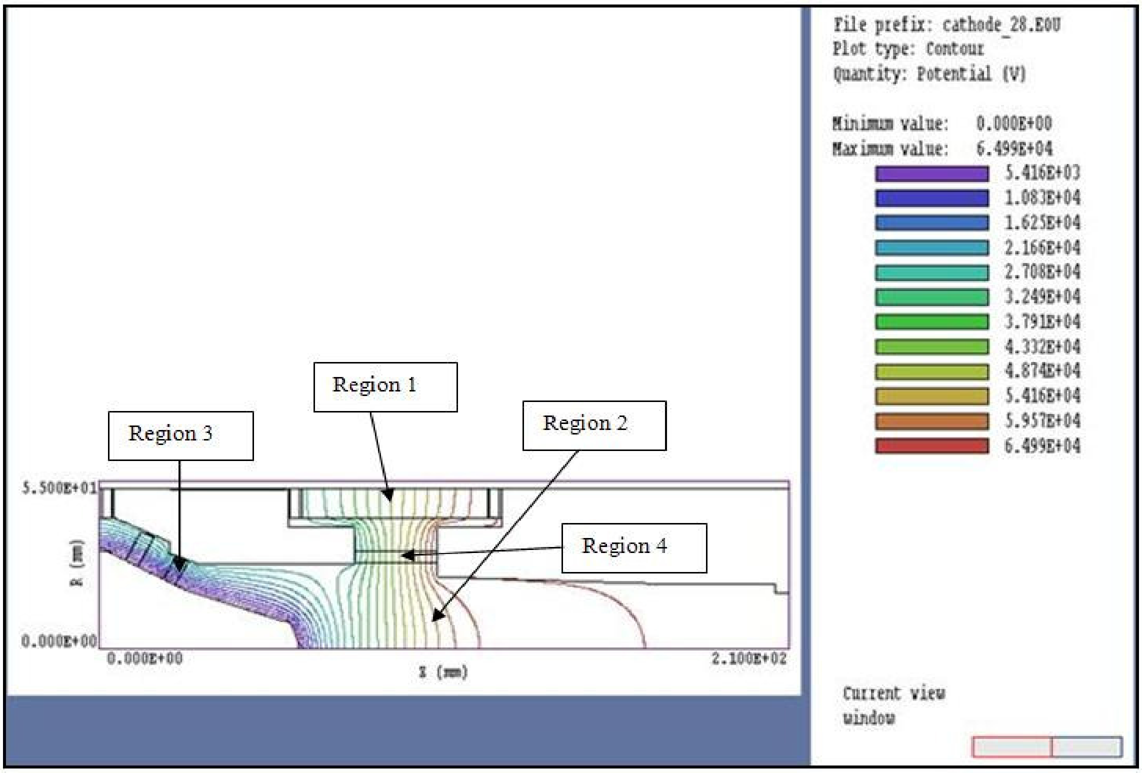

Fig. 4 — Electric potential profile in MIG using TRAK

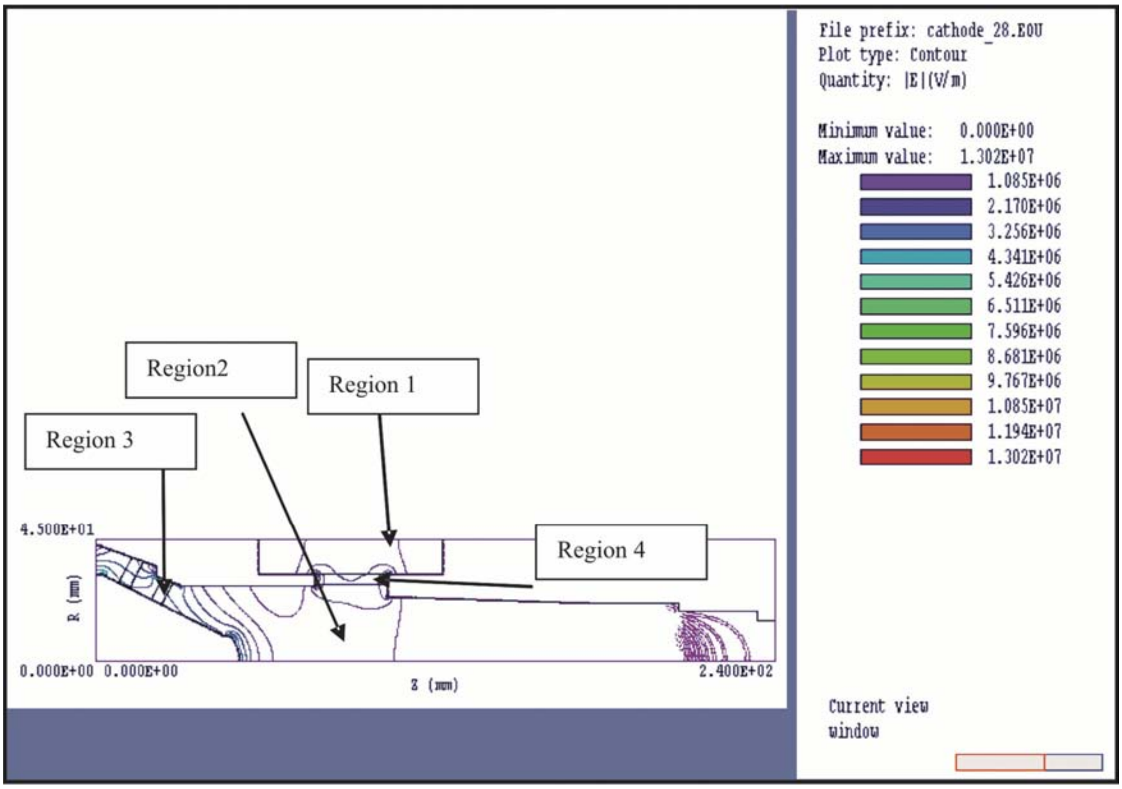

Fig. 5 — Electric field profile in MIG using TRAK

regions in the structure have been used. The critical regions represented as 1, 2, 3 and 4 respectively (Fig. 3), where region 1 is the space between modulating and control anodes where ceramic is used, region 2 is the vacuum gap in MIG, region 3 is the minimum vacuum gap space between cathode and modulating anode and region 4 is the vacuum space between modulating and control anodes below the ceramic. All the edges in the gun geometry have been chamfered to avoid the excess electric field.

The potential and electric field values obtained from TRAK are shown in Figs 4 and 5, respectively, for the MIG for 42 GHz gyrotron. Table 2 presents the values of these parameters in different regions of MIG and it is very clear that the design of MIG by using EGUN code is safe from voltage breakdown point of view, since the achieved values of electric field intensity are within the breakdown criteria which is 5kV/mm as the maximum value of electric field in vacuum (Table 2).

2.1 Sensitivity analysis of MIG for high voltage breakdown

As during the fabrication and processing of the device, it is very difficult to maintain the original parameters that cause the high voltage breakdown. So it is necessary to analyse the effect of potential increment on electric breakdown. Keeping this aspect in mind, a thorough sensitivity analysis of MIG has been carried out from the high voltage point of view.

Two cases have been studied for sensitivity analysis. In first case, the modulating anode voltage has been kept constant and the accelerating anode voltage has been varied. While in the second case, accelerating anode voltage has been kept constant and modulating anode voltage has been varied.

By changing the accelerating anode voltage, studies related to the different regions have been carried out to see the nature of electric field intensity. Figures 6 and 7 show the variation of electric field intensity at different regions by changing the accelerating anode voltage from its actual value 65 kV by keeping modulating anode voltage 29 kV unchanged. Here, the accelerating anode voltage is taken along the *x*-axis and electric field for different regions is taken along *y*-axis. By increasing accelerating anode voltage from 65 to 110 kV, the value of electric field intensity increases for three regions 1, 2 and 4, respectively. Although for regions 1 and 4, the electric field intensity is well below the breakdown limit (Fig. 6) but, for region 2 it reaches the breakdown limit (Fig. 7). Here, the electric field variation for region 3 is not shown in the Fig. 7. This is because the electric field intensity is almost unchanged.

Similarly, sensitivity analysis has been carried out with respect to modulating anode voltage to see its effects on electric field intensity at different regions

Table 2 — Electric potential and electric field values in the different regions of MIG

Region No.	Region 1	Region 2	Region 3	Region 4
Medium	Ceramic	Vacuum	Vacuum	Vacuum
Potential difference (kV)	63.87	65.00	29.00	65.00
Electric field (kV/mm)	0.78	6.44	5.47	3.81

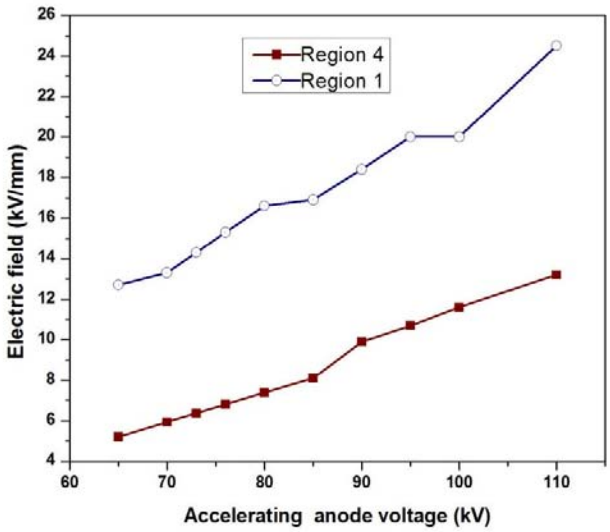

Fig. 6 — Effect on electric field intensity by variation of accelerating anode voltage [V_a = 29kV]

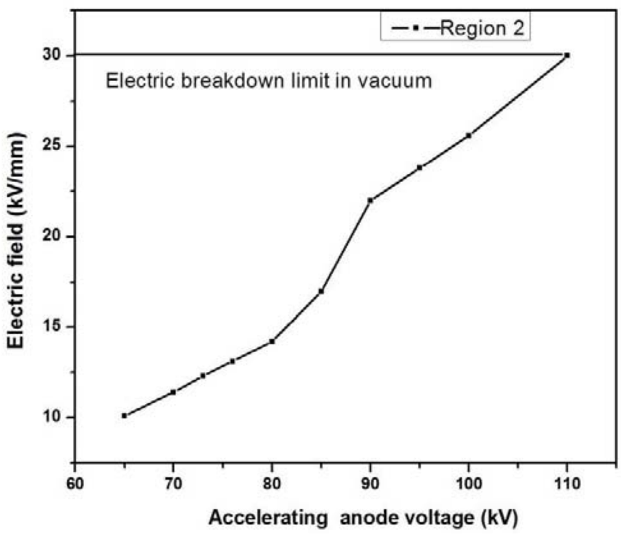

Fig. 7 — Effect on electric field intensity by variation of accelerating anode voltage [V_a = 29kV]

(as indicated in Fig. 5) and results are shown graphically in Figs 8-10 for region 2, region 3 and regions 1and 4, respectively. The modulating anode voltage is kept along *x*-axis while electric field for different regions is taken along *y*-axis.

From Figs (8-10), it is clear that, if modulating voltage is increased from 29 to 60 kV, the value of electric field intensity is increased linearly for the regions 2 and 3, respectively, while the value of electric field intensity is decreased for the regions 1 and 4, respectively. So, it is found that, for all regions, the electric field intensity is well below the breakdown limit.

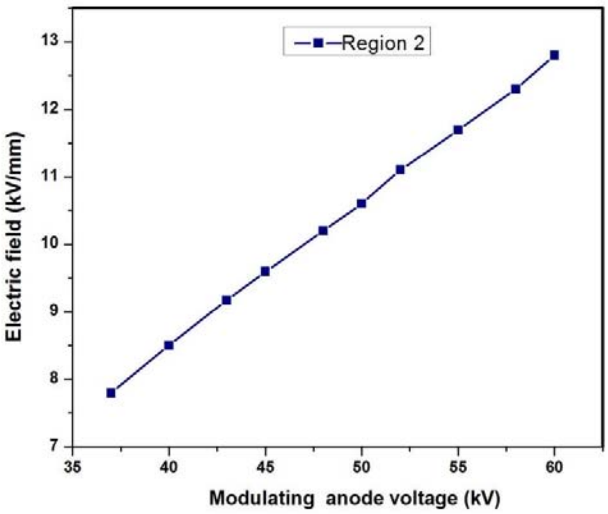

Fig. 8 — Effect on electric field intensity by variation of modulating anode voltage at region 2 [V_o = 65 kV]

3 High voltage Analysis of MIG for 120 GHz 1 MW Gyrotron

Similarly, to avoid the voltage break down between the two electrodes, the high voltage analysis of MIG for 120 GHz 1MW gyrotron has also been carried out with the help of the software TRAK. The MIG for 120 GHz, 1 MW gyrotron has been designed by using EGUN code[12]. The designed MIG parameters obtained from MIG design have been used to model the MIG by using TRAK code for high voltage analysis. The various parameters used for modeling of MIG (Fig. 11) are given in Table 3. To avoid the excess electric field at different edges in the MIG structure, especially at critical regions, all the edges have been chamfered. There are some critical regions where the chance of voltage breakdown is prominent. Thus to avoid the electric breakdown in these regions, the potential and electric field profiles have been plotted by using TRAK code and the value of electric field intensity has been estimated.

Figures 12 and 13 show the electric field and potential profiles, respectively. The different critical regions have been represented as 1, 2, 3 and 4. The values of electric field intensity and potential at different regions as indicated in Fig. 12, are given in Table 4 and it is very clear that the design of MIG by using EGUN code is safe from voltage breakdown point of view, since the achieved values of electric field intensity are within the breakdown criteria which is 5kV/mm as the maximum value of electric field in vacuum (Table 4).

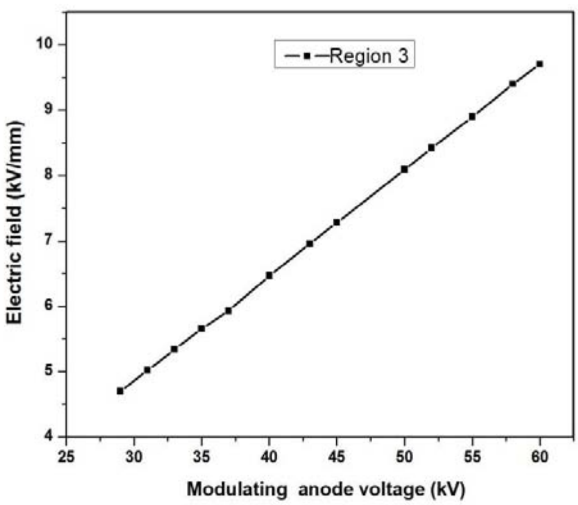

Fig. 9 — Effect on electric field intensity by variation of modulating anode voltage at region 3[V_o = 65 kV]

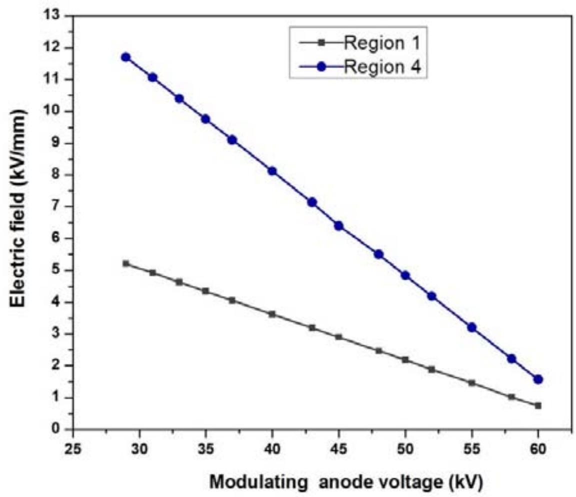

Fig. 10 — Effect on electric field intensity by variation of modulating anode voltage at region 1 and 4 [V_o = 65 kV]

Table3 — Various parameters used to model the MIG by using TRAK

Cathode radius (r_c)	49 mm
Slant length of cathode (l_s)	3.84 mm
Modulating anode voltage (V_a)	60 kV
Accelerating anode voltage (V_0)	80 kV

Table 4 — Electric potential and electric field values in the different regions of MIG

Region No.	Region 1	Region 2	Region 3	Region 4
Medium	Ceramic	Vacuum	Vacuum	Vacuum
Potential difference (kV)	80.00	80.00	79.64	60.00
Electric field (kV/mm)	0.54	2.20	9.43	8.25

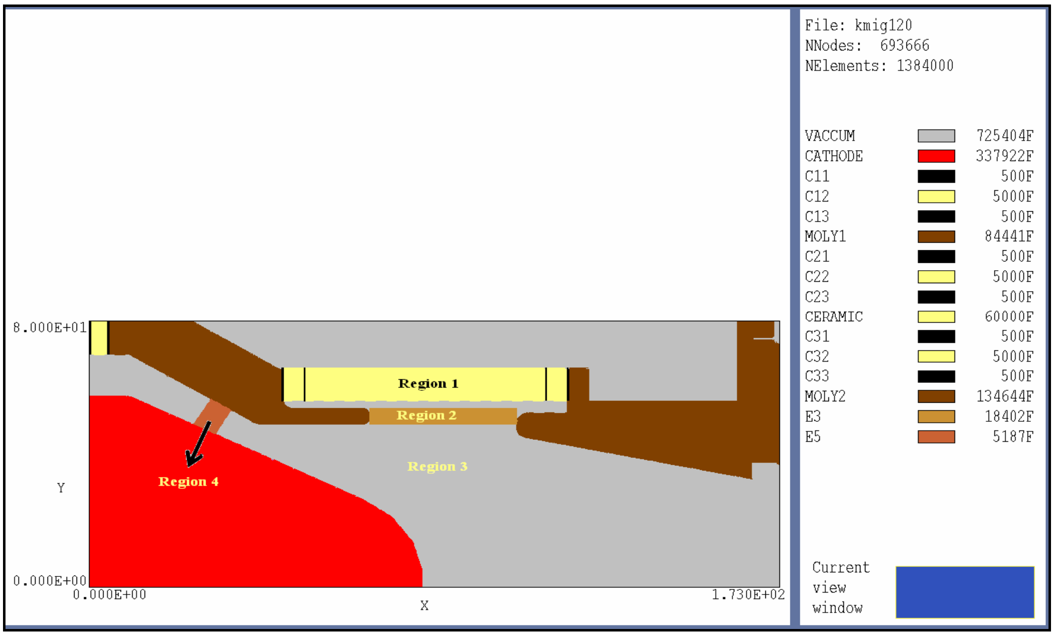

Fig. 11 — 2D Axis-symmetric model of MIG modeled in TRAK code

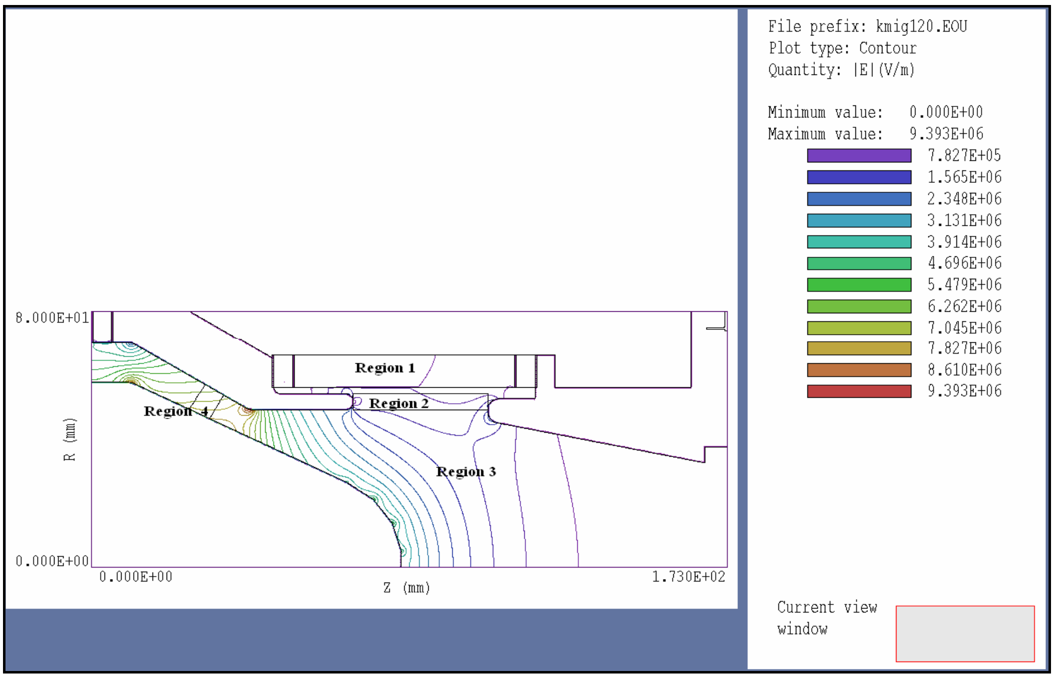

Fig. 12 — Electric field profile in MIG using TRAK

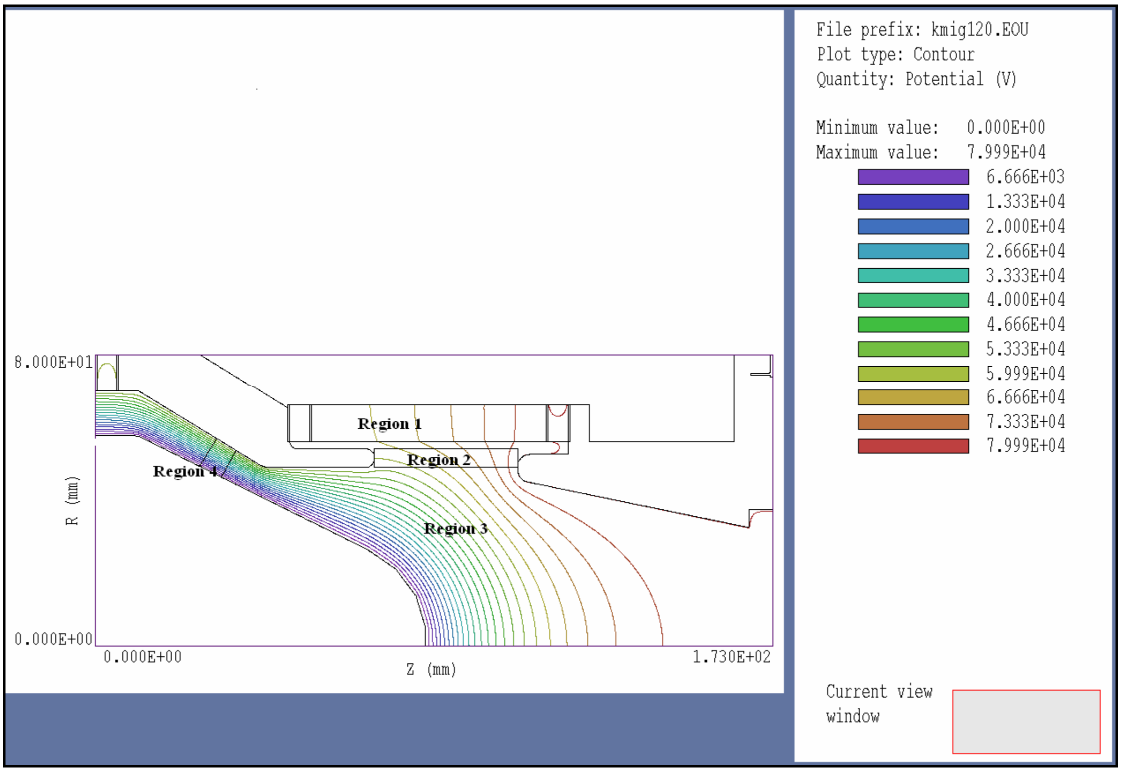

Fig. 13 — Electric potential profile in MIG using TRAK

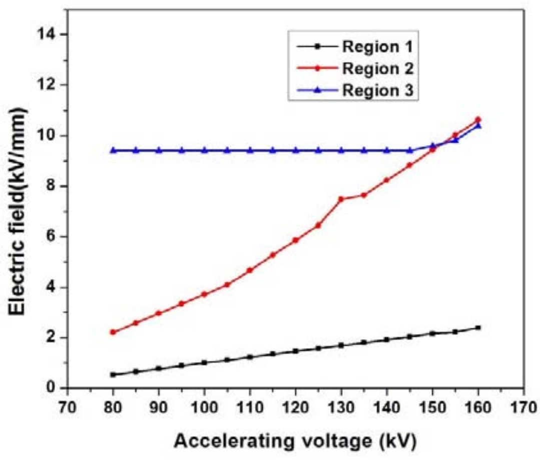

Fig. 14 — Effect on electric field intensity by variation of accelerating anode voltage [$V_o = 65$ kV]

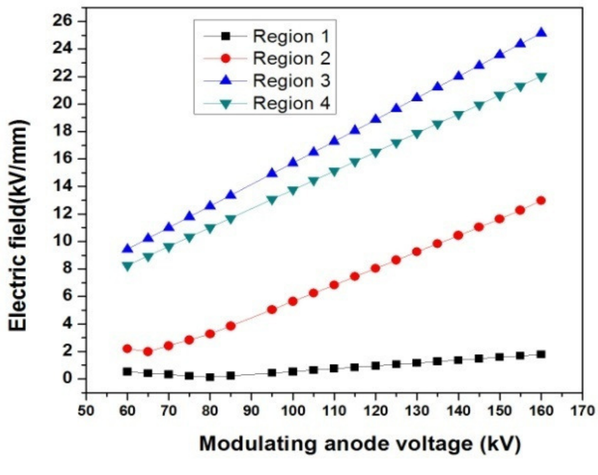

Fig. 15 — Effect on electric field intensity by variation of modulating anode voltage [$V_o = 65$ kV]

3.1 Sensitivity Analysis of 120 GHz MIG for High Voltage Breakdown

Sensitivity analysis of different breakdown regions in MIG has been carried out to see the breakdown voltage. Here also two cases have been studied. In the first case, the modulating anode voltage has been kept constant and the accelerating anode voltage has been changed from its actual value i.e. 80 kV to 160 kV. Fig. 14 shows the variation of electron field intensity by changing the accelerating voltage from 80 to 160 kV. For all the three regions, the electric field intensity increases with increase in accelerating anode voltage. The fourth region has not been shown in Fig. 6-15 because the electric field intensity is almost unchanged in this region.

In second case, the variation of electric field intensity has been analyzed with respect to the modulating anode voltage by keeping the accelerating anode voltage fixed. Figure 15 shows the electric field intensity variation with respect to modulating anode voltage. From Fig. 15, it is clear that when the modulating anode voltage is increased from 60 to 160 kV, the value of electric field intensity for all the regions is increased. From the electric breakdown point of view, it is more sensitive for regions 3 and 4 than 1 and 2 regions.

4 Conclusions

The high voltage analysis of MIG for both low power (42 GHz, 200 kW) and high power (120 GHz, 1 MW) gyrotrons has been presented in this paper. This analysis has been carried out to avoid the electric field breakdown at different critical regions of MIG. For the high voltage analysis, a commercial available software TRAK has been used. Based on these analyses, it can be concluded that both the MIG designs are safe from the high voltage point of view.

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