

Effect of surface roughness on the electrostatic field of an RPC

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Abstract. The inner surfaces of the electrodes encompassing the gas volume of a Resistive Plate Chamber (RPC) have been found to exhibit asperities with three kind of feature grossly. The desired uniform electric field within the gas volume of RPC is expected to be affected due to presence of these asperities, which will eventually affect the final response from the detector. In this work, an attempt has been made to model the highly complex roughness of the electrode surfaces and compute its effect on the electrostatic field within RPC gas chamber. The different aspects of surface structures have been modeled and their effect on the electrostatic field has been calculated. The calculations have been performed numerically using Finite Element Method (FEM) and Boundary Element Method (BEM) and the two methods have been compared in this context.

1. Introduction

The Iron CALorimeter (ICAL) setup at India-based Neutrino Observatory [1] will be able to track the muons produced by the interaction of neutrinos with the iron, used as the target material, and produce information necessary for studying different parameters of neutrino oscillation and mass hierarchy. This will be achieved by deploying about 29,000 Resistive Plate Chambers (RPC) of dimension $2\text{ m} \times 2\text{ m}$ as its active detector elements, the response from which will provide information about the position and the timing of the passing muons. The requirement of large area coverage combined with muon detection with good position ($< 1\text{ cm}$) and timing resolution ($< 1\text{ ns}$) disapproves non-uniform response from any part of the detector which may affect the overall performance of the setup. Long term stability in the detector performance is another important requirement in general. All these call for a detailed investigation on the detector response and understanding its dependence on factors like device geometry, material grade, gas mixture etc. including environmental parameters.

An extensive study of the electric field of the detector can pave a way to evaluate the response as it depends critically on the field configuration for a given gas mixture and environmental conditions. As the device geometry and the material are the fundamental configuring parameters of the field for a given potential, the imperfections or artifacts in the design and the material are likely to distort the electric field locally depending on their nature. Glass or bakelite is commonly used for making the resistive plates in an RPC and it has been found to develop



some asperities (typically $< 10\mu\text{m}$) on its surface in the process of production and handling. The long term operation of the RPCs may also contribute by affecting the surface through various chemical processes. Depending on their shape and dimension, these asperities may give rise to spark, dark current etc. and thus lead to gradual degradation of the detector. In many cases, several methods of surface treatment have been adopted to cure the roughness or a better grade (better surface planarity) has been used instead. So, a detailed study on the effect of rough surface on the field configuration deems necessary in deciding the acceptable value of roughness as well as prediction and interpretation of the experimental data. In the present work, numerical simulation has been used to estimate this in case of a bakelite-RPC. The RPC has been modeled following the design parameters of a prototype fabricated for INO R&D work. The asperities on the inner surface of the bakelite electrode have been configured on the basis of the measurement of surface profile of the same bakelite grade used for building the prototype. The calculation has been performed following two numerical methods, namely, Finite Element Method (FEM) and Boundary Element Method (BEM).

In the following, section 2 describes the details of the modeling of the surface roughness based on the measurements and their implementation in the software. The results are discussed in Section 3 and the summary of the work can be found in Section 4.

2. Surface Morphology & Numerical Modeling

An RPC [2] is basically a parallel plate configuration comprising of two resistive plates encompassing a gas volume. A potential difference across the gas volume is applied through a conductive coating used on the outer surface of the plates. Two sets of mutually orthogonal readout strips are placed on either sides of the parallel plate configuration to collect the signal induced by the passage of muons through the gas volume. The design of the bakelite-RPC prototype has been discussed in detail in a previous work where the effects of various geometrical components on the electric field have been evaluated [3]. In the following, the measurements of the surface morphology of the P-120 grade and the numerical modeling of the asperities will be discussed.

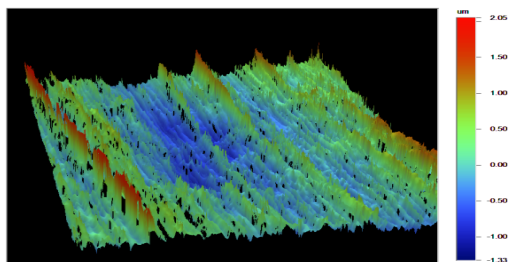


Figure 1. Surface roughness :
 $R_a = 158.15 \text{ nm}$, $R_t = 1.73 \mu\text{m}$.

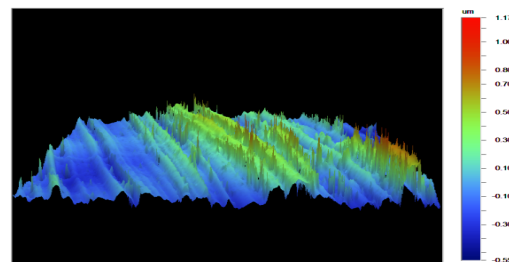


Figure 2. Surface roughness :
 $R_a = 282.04 \text{ nm}$, $R_t = 3.37 \mu\text{m}$.

2.1. Surface Morphology

The imaging of a P-120 bakelite sample has been done using BRUKER ContourGT-K 3D optical microscope. A few sampling has been made at several locations with scanning area of dimension of $640 \mu\text{m} \times 480 \mu\text{m}$ (shown in figures 1 and 2, for example). It is evident from the data that the average roughness of the surface, represented as R_a , varies between 150 - 300 nm while the range, R_t (distance between the peak and the valley) lies between 1 - 5 μm . By close inspection, following three gross structures have been found as asperities on the surface: (a) spike, (b) ridge and (c) wave. In the present work, only the effect of their shapes have been analyzed without considering their spatial distribution.

2.2. Numerical Modeling

To use the computational resources economically, a simplified model of RPC with dimension $5\text{ cm} \times 5\text{ cm}$, consisting of only the bakelite plates and the conductive coats have been considered while the said asperities have been distributed on the inner surface of the upper bakelite plate following a definite pattern. A voltage difference of 12 kV has been applied between the coats on either sides. The three features of the rough surface along with their modeling scheme have been discussed below:

- (i) Spike - The randomly distributed spikes have been modeled using boxes of different heights and widths although with a periodic distribution. The smallest box has a cross-section of $1\text{ }\mu\text{m} \times 1\text{ }\mu\text{m}$ and height 250 nm.

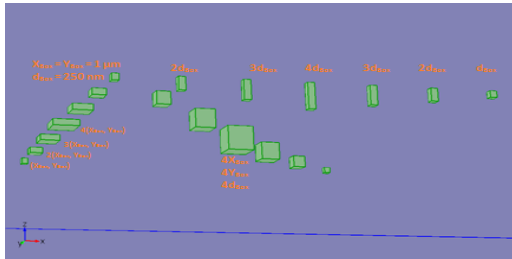


Figure 3. Surface roughness of spike-like structure modeled using a distribution of boxes of different heights and widths.

$\mu\text{m} \times 1\text{ }\mu\text{m}$ and height 250 nm. Boxes with height in multiples of that of the smallest box have been placed along X-direction while those with width in multiples of the same of the smallest one have been arranged along Y. Both the height and the width of the boxes have been increased to a maximum limit of $1\text{ }\mu\text{m}$ and $4\text{ }\mu\text{m}$, respectively, and then reduced again to reach the smallest values along the respective directions. The space between the edges of any two consecutive boxes has been made $8\text{ }\mu\text{m}$ for computational convenience which will be discussed later. For another series of boxes, placed along the diagonal, both the height and width have been increased in multiples of the smallest box and reduced back to the smallest values. The reason behind the scheme (shown in figure 3) has been to study the individual as well as the combined effect of the variation in height and width of the box in a systematic way.

- (ii) Ridge - Presence of some ridge-like structures with sharp heads can be seen in figure 1. This kind of structure has been modeled using five triangular prism-like blocks placed on the inner surface of the upper plate with their sharp edges facing the gas volume. The ridges

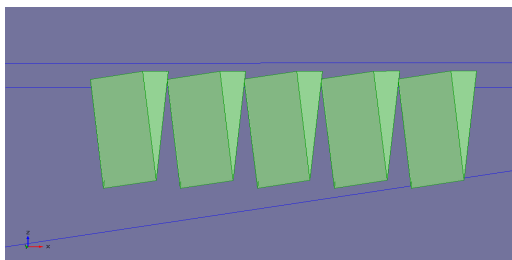


Figure 4. Surface roughness of ridge-like structures modeled using a series of triangular prism-like blocks.

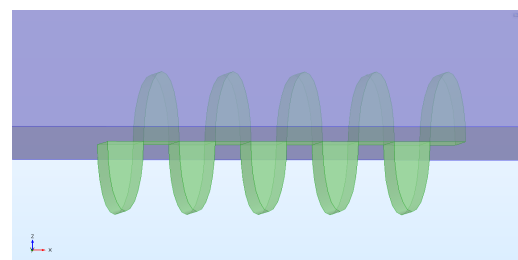


Figure 5. Surface roughness of wave-like structure modeled using a sinusoidal wave.

have been placed parallel to each other along the X-direction. The height, base cross-section and pitch of the ridges are $5\text{ }\mu\text{m}$, $25\text{ }\mu\text{m} \times 650\text{ }\mu\text{m}$ and $50\text{ }\mu\text{m}$ respectively. The model is shown in figure 4.

- (iii) Wave - The surface profile measurement has also exhibited a wave-like feature as can be seen from figure 2. It has been modeled in the shape of a sinusoidal wave having amplitude of $10\ \mu\text{m}$ and a wavelength of $40\ \mu\text{m}$ as shown in figure 5. The width of the wave is $20\ \mu\text{m}$. The roughness feature has been incorporated on the upper bakelite plate as mentioned in earlier case. Obviously, the trenches of depth $10\ \mu\text{m}$ have been implanted on the plate material.

2.3. Numerical implementation

Two different toolkits have been used to compute the field map, COMSOL Multiphysics® [4] v5.2 and neBEM [5] v1.8.16 which calculate the field following FEM and BEM respectively. In COMSOL®, the whole geometry has been meshed using free tetrahedral elements except the conductive coating region which has required a special treatment due to its very small thickness [3]. Different sizes of the elements have been used to mesh different parts of the geometry depending on their dimensions. In neBEM, the surfaces of the geometry have been discretized

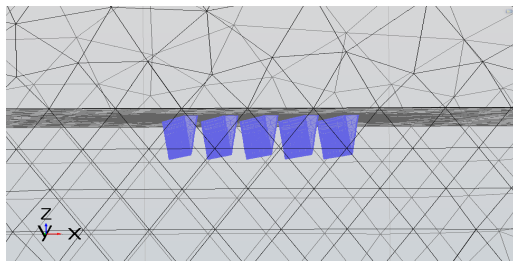


Figure 6. The ridge-like structure meshed in COMSOL®.

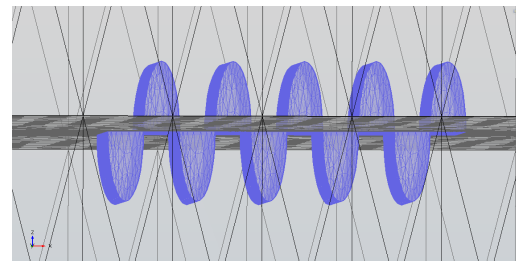


Figure 7. The wave shaped structure meshed in COMSOL®.

using rectangular or triangular elements according to the shape of the geometrical components. The geometry has been built in Garfield [6] using Constructive Solid Geometry (CSG) approach. The charge distribution on these smaller elements has been calculated using Green's function technique from the supplied boundary conditions. The potential and field at any point have been calculated directly from this charge distribution using the same Green's function technique.

Closer placement of rough structures has required a finer mesh to resolve the geometry which in turn has increased the consumption of computational resources. In modeling the spike-like structures, the boxes have been placed $8\ \mu\text{m}$ away from each other as an optimum value of separation. Another difficulty in solving the models arises due to the presence of sharp edges, whose effect can be observed only by using infinitesimally small mesh. Figures 6 and 7 have shown the three dimensional meshing scheme in COMSOL® for the ridge and the wave-like structures respectively. Figure 8 has shown the two dimensional scheme of discretization, used by neBEM to solve the ridge-like structure.

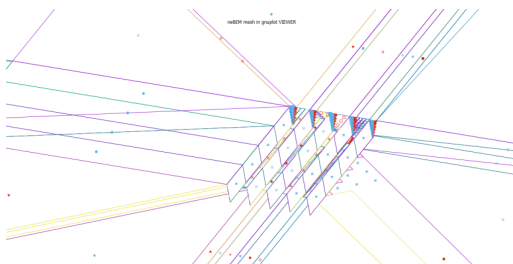


Figure 8. The ridge-like structure discretized using triangular and rectangular elements in neBEM.

3. Result

Here the results of the electric field computed by COMSOL[®] and neBEM have been discussed. All the plots have shown the variation in the value of Z-component of the electric field (E_z) for different features of the surface roughness as this is the major component of electric field which can affect the RPC response.

3.1. Spike

The effect of the box structures having different width on the electric field can be seen from figure 9 where the variation of E_z along the Y-direction has been plotted. The calculation has been performed at several locations away from the box and compared in the figure. The following

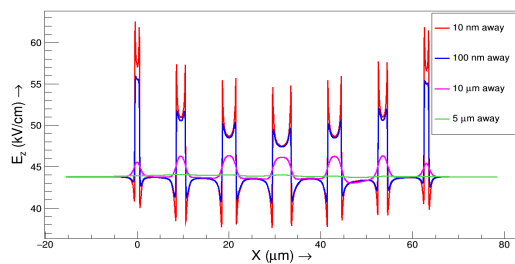


Figure 9. E_z Vs Y plot from neBEM for different distances from the smallest box.

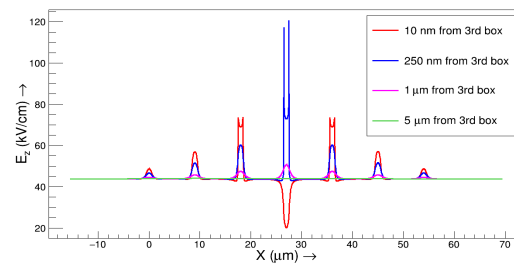


Figure 10. E_z Vs X plot from neBEM for different distances from the third box.

observations can be made from the plot: (a) The field value is enhanced at the positions of the boxes, (b) The magnitude is larger when the box is narrower in width, (c) A sharp rise occurs along the edges of the boxes, (d) All these effects get more pronounced in close vicinity of the boxes. The field is found to increase by 30.5% maximum at 10 nm away and can rise upto 42.8% at the edges while it falls close to the regular value (within 0.6%) around 5 μm . The effect of height of the box structures can be analyzed from figure 10 where the variation of field values calculated along the X-direction and at several positions away from the third box have been shown. As evident from the figure, the observations are similar to that made in earlier case. It is to be noted that in case of the highest box (at the center of the distribution), a dip on the line of 10 nm has occurred as it cuts through the box. From these two plots it can be concluded that the taller and narrower spikes will affect the field most, though the affected region will stretch with the increase in width.

3.2. Ridge

The effect of the ridge on the electric field as calculated at different distances away from the head of the ridge has been shown in figure 11. The enhancement in field value reduces as one goes away from the ridge structures as is evident from the figure. The field value can change by 46.2% to 0.6% in a range from 10 nm to 50 μm away from the structures. The contour plot of E_z in the vicinity of these ridge-like structures can be seen from the figure 12 as calculated using COMSOL[®].

3.3. Wave

The change in the value of E_z along lines at different distances from the wave peaks has been shown in figure 13, calculated using COMSOL[®]. The effect of this wavy structure extends upto 50 μm away from the peaks where the relative deviation in the field with respect to its normal or regular value reduces to 1.9% only while it is 59.2% within 10 nm of the peak and - 21.2% at

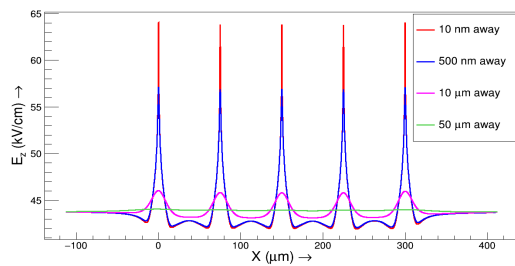


Figure 11. E_z Vs X plot along the lines at different distances from the edges of the ridges from neBEM.

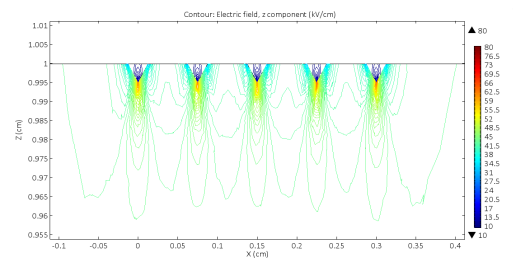


Figure 12. Contour plot of E_z in X - Z plane from COMSOL®.

the troughs. Figure 14 shows the surface contour plot of the E_z values 100 nm away from the peaks as has been computed with the COMSOL®.

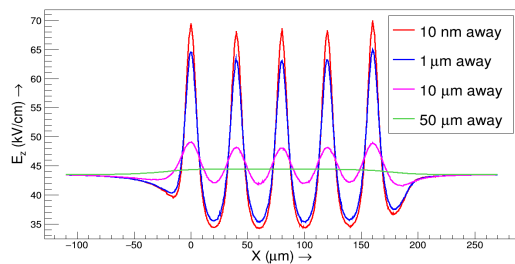


Figure 13. E_z Vs X plot from COMSOL® at different distances from the peaks of the wave.

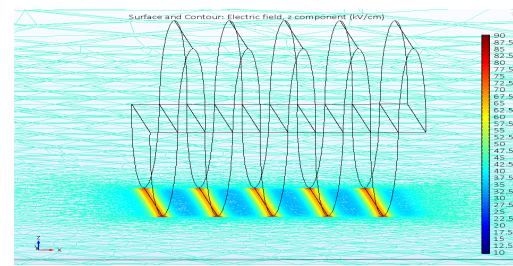


Figure 14. Contour plot of E_z from COMSOL® on the surface, 100 nm away from the peaks of the wave-shaped profile.

3.4. Comparison of FEM and BEM

The computation of E_z has been performed using two solvers and compared. Table 1 shows a comparison between these two methods in terms of different parameters to solve the case of spike-like structures (see figure 3) as an example. The second column of the table shows the number of total elements used for meshing the geometry. The third and fourth columns show the time taken to solve the problem and the system memory used during that process respectively. In case of COMSOL®, the quoted values are the ones that have been taken by the solver while using the optimized meshing scheme. The process of finding out the optimum meshing scheme itself may be a time-consuming affair for COMSOL® while for neBEM, it is significantly simpler. The fifth column of the table shows the convergence criterion for COMSOL® which is the relative error (R.E.) in the calculated values with respect to the set limit (10^{-5} here) for the last two iterations. COMSOL® has required to iterate 190 times to achieve this. For neBEM, the error has been estimated by finding out the deviation in the calculated values at the collocation points with respect to the given values as obtained from the boundary conditions. The maximum error has been found to be 10^{-4} on one of the elements in this case.

4. Summary

The electrostatic field map for different features of surface roughness of bakelite plate in an RPC has been computed using two solvers following different methodology. The value of the

Table 1. Comparison of FEM and BEM using different parameters.

Solver	Elements	Time	Memory	Error/Convergence
COMSOL [®]	2×10^6	15 mins	~ 4 GB	R.E. = 10^{-5} in 190 iterations
neBEM	17×10^3	2 hours	~ 8.8 GB	Maximum = 10^{-4}

electric field near the asperities increases to 60% at the most of the regular value depending on the shape and size of the asperities. The distortion in the field is found to be confined within a small region (10 - 200 μm). This distorted field map is likely to affect the gas transport properties and production of avalanche close to the resistive plates and alter the detector behavior. Considering the overall distribution of asperities on the surface, the detector response near the plates may be significantly altered which in turn may affect the physics performance of INO ICAL detector. The roughness properties of the RPC plates need to be investigated. The plates should be made to undergo surface treatment, depending on the results of the surface study.

References

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