Calculations Based on Measurements of Charge Deposited by a Streamer on a PTFE Surface

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Abstract

Surface charge on an insulator's surface is studied using 3-dimesional finite element modelling. The calculations are based on measurements of surface charge deposited by a streamer on a PTFE surface. The surface electric field strengths associated with uniform surface charge density distributions over a 1mm^2 region are calculated for a range of different measured charge densities. The effect of reducing the area of the surface charge whilst keeping the total amount of charge in the region constant, is observed. The surface charge is then modelled with a Gaussian distribution of charge and compared to that of a uniform distribution. By assuming a maximum allowable surface electric field strength an estimation of actual charged path diameter is made.

1. Introduction

A high resolution electrostatic probe technique for the measurement of densities of charge on insulator surfaces has been described in a previous paper [1]. It has been used to investigate the corona propagated over a PTFE surface from a rod electrode under an impulse voltage. The resolution is sufficient to permit measurement of the charged paths deposited by individual streamers. The present paper reports on such a measurement; finite element modelling of the surface charge allows the electric field strengths involved to be calculated, providing an insight into the nature of surface discharges and, in this case, an estimate of the path diameter.

2. Modelling Surface Charge

Surface charge densities are measured in planar coordinates. For finite element modelling, the OPERA-3d system (Vector Fields Inc.) has been used. This specifies the use of volume charges, so that in order to compute fields due to surface charges, very thin three-dimensional volumes had to be defined. For the deposited surface charges considered here, the thicknesses would be on a molecular scale. The applicability of the system was therefore investigated using the model shown in Figure 1 where a very thin element of uniform positive charge density, was positioned on the surface of an insulator placed between two earthed electrodes 10mm apart.

The electric field along a vertical path (Figure 1) on the surface passing symmetrically through the element was then computed for thicknesses of element ranging in steps from 1mm down to 1μm. It was found that the surface electric field strength tended to a limit as the thickness was decreased, when a constant planar charge density was used for all thicknesses. A change of thickness from 10μm down to 1μm resulted in an increase of field at the edge of the element, where it was a maximum, of about l per cent. In all the models used here, therefore, the region of surface charge was set at an assumed thickness of 0.1μm.

The electric field set up by the uniform region of surface charge is illustrated in Figure 2. The length and direction of the arrows indicate respectively the magnitude and direction of electric field on the insulator surface. Magnitudes are greatest at the edges of the element; the fields are lower at the centre of the element due to the screening effects of the surrounding charge. A relative permittivity of 2.2, characteristic of PTFE was used in the calculations.

The magnitude of the electric field strength through the centre of the charged region along the surface is plotted in Figure 3 for different assumed charge densities. The greatest field strengths are clearly visible at the edges.

3. Measured Charge in a Streamer Channel

The scanning system for charge density measurement, described elsewhere [1] has a spatial resolution 1mm square. By scanning across the charge deposited on PTFE by the ends of streamer channels, a maximum density of 10pCmm^{-2} has been obtained; this occurred about 2mm from the tip. Figure 3 shows that if this charge were to be deposited over a 1mm^2 region, the resulting electric field would not exceed 300kVm^{-1}. However, the measured charge is not distributed uniformly, but is localised within the 1mm square along a thin channel of Length 1mm. Thus, the observed density corresponds to that of a linear charge of 10pC along 1mm length of channel at its tip.

4. Streamer Width

Several estimates have been made of streamer channel widths (for example [2] [3]). To study the effect that streamer channel width would have, in the present case, on the localised surface field strength, a portion of streamer channel has been modelled with an assumed charge density of 10pC per mm length. The model has been based on that shown in Figure 1. The 1mm^2 element studied earlier was replaced with a 1mm length of streamer channel as shown in figure 4. Using different numbers of 10μm wide strips charge density streamer channels of width 20μm to 100μm could be simulated. To maintain a net (total) positive charge of 10pC on the 1mm length of streamer channel the applied surface charge density was increased as the channel width decreased. The values of charge density used are shown in Table 1.

One of the limitations of the modelling software was that it only allowed *uniform* charge distributions in each region. The model shown in Figure 4 could overcome this limitation by applying different charge densities to each of the streamer channel strips at once. This allowed simple non-uniform charge distributions to be simulated within the streamer channel.

Charge densities were applied to produce a Gaussian distribution of charge in the streamer channel while maintaining a total charge of 10pC per mm length. This is illustrated in Figure 5.

The charge density appeared normally distributed through a cross section of the channel. This is a much more realistic model of a streamer channel, since in practice a streamer will not deposit charge in a region with exact boundaries.

Figure 6 gives a view of the fields calculated for three different streamer channel cross-sections. The first two cases have completely uniform charge distributions within 20µm and 100µm width channels. The third case is the Discrete-Gaussian distribution. All three cases contain 10pC of charge per millimetre length.

Figure 6(b) shows the electric field in air produced by the modelled streamer channel. The field strength is strongest at the edges of the uniform distribution cases, but for the Gaussian distribution the field is strongest at the centre. Figure 6(c) shows the magnitude of the electric field strength along the surface. For the Gaussian distribution local maxima and minima can be seen at the boundaries of the nested regions. If a truly continuous variation of charge density could be modelled within the streamer channel then these perturbations would disappear.

Figure 7 shows the resultant surface electric field through the centre of the streamer channel for all the different channel widths modelled. The thin streamer channels produce very high electric fields. For 10pC over a 1mm×20μm region, fields of over $20MVm^{-1}$ are present. This is clearly an unfeasible situation because the distribution would blow itself apart or cause further ionisation; in either case the streamer channel would not be stable.

Figure 7 also shows the field produced by the Gaussian distribution of charge. The maximum field strength is found at the centre of this distribution; not at the edges as with the uniform distribution cases. The Gaussian distribution is probably the more natural distribution because discrete boundaries at the edges of the channel cause large field enhancements, and would be expected from the dynamics of the formative avalanches.

The peak value of the Gaussian distribution corresponds approximately to the field at the centre of a 50μm diameter streamer channel with discrete boundaries. Hence the Gaussian distribution modelled can be said to have an effective diameter of approximately 50μm. This is very close to the 45μm half width of the Gaussian charge distribution itself (see Figure 6(a) CASE C). These two values may in fact be the same; the difference caused by the discretisation of the distribution.

If this is true then the magnitude of the field strength at the centre of a uniform distribution can be used as the maximum value of an equivalent Gaussian distribution. The magnitude of the electric field strength perpendicular to the surface on the central axis of the uniform distribution streamer channels is plotted against streamer width in Figure 8.

The values of surface electric field strength follow very closely the curve shown in Figure 8. The best fit equation for the curve was $E = 384/w$, where E is the electric field strength with units of MVm^{-1} and w is the streamer width with units of μm. Substituting a value of $3MVm^{-1}$ for the field strength that causes ionisation in air into the equation gives a minimum streamer channel width of about $130\mu m$.

5. Discussion

The path measured by this technique was created by the net charge deposited by a streamer which has grown in air in close proximity to the PTFE surface a process which is known to be influenced by the surface [4]. It is close to the end of its trajectory. A net positive charge is recorded, since in this region free electrons move relatively rapidly from the streamer head into the streamer trail, resulting in a relatively small negative charge density. The path width of $130\mu m$ is very close to the upper limit of estimates of previous researchers of streamer channel diameters in air which ranged between 25 and $125\mu m$ [2-6]. However some uncertainties, inherent in the measurements, must be considered.

For example, an unknown degree of lateral charge migration may have occurred on the surface, due to the self-field of the deposited charge. Thus the diameter of the originating streamer may, in general, be smaller than the width of the measured charge. Sone et al. [5] show an example of a streamer recorded by a liquid crystal technique, in which the electrostatic stress causes a deformation of the liquid crystal surface. This gave a diameter of $100\mu m$, but the electric field in this experiment had a large component perpendicular to the surface.

Again, the present measurement is of a net density of charge. This rises to a maximum about 2mm from the tip. Free electrons from the streamer head are likely to suffer attachment to form negative ions, according to the relation:

$$n = n_0^{-\eta x} \qquad \textbf{(1)}$$

Here η is the electron/molecule attachment coefficient. n is the electron density at distance x from the streamer head, where the density is n_0. Taking an estimated attachment coefficient η of 0.5 per mm per electron, about 23 per cent of electrons will have formed negative ions at a distance of 2mm. These are relatively immobile, so that to give the observed net charge density, the positive charge density must be increased by at least this amount. A further increase would be postulated if significant attachment of electrons also occurred directly to the surface [4][6]. Within the same distance, significant electron-positive ion recombination would also occur, so that the actual positive ion density deposited on the surface would again be larger than the measured value.

However, the assumption of a maximum field of 3MVm^{-1}, which determines the derived radius, is unaffected by the composition of the deposited charge. Hence, it can be said that the 130µm limit for the charged path width is the minimum width if the charge is distributed with a Gaussian cross section.

6. Conclusion

A scanning technique has been used to measure the density of the charged path deposited by a streamer in a corona passing over a PTFE surface in air. On the assumption that the electric field set up at the edge of the charge cannot exceed the value that would cause ionisation, a value of path width of 130μm has been deduced. Similarities between this result and those of other researchers suggest that this value may be close to that of the streamer itself.

7. Acknowledgements

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8. References

1. **D. C Faircloth and N. L. Allen,** “High Resolution Measurements of Surface Charge Densities on Insulator Surfaces”, Submitted IEEE Trans. Dielectrics and Electrical Insulation, 2002.
2. **G. A. Dawson and W. P. Winn,** “A model for Streamer Propagation”, Z. Physik. 183, 159-171, 1965.
3. **Y. Muroakha, T. Takada and K.Hidaka,** “Nanosecond Surface Discharge and Charge Density Evaluation Part 1: Review and Experiments”, IEEE Electrical Insulation Magazine 17, pp. 6-16, 2001.
4. **H. F. A. Verhaart, J. Tom, A. J. L. Verhage and C. S. Vos,** ”Avalanches Near Solid Surfaces”, Proc. 5th Int. Symp. on High Voltage Engineering, Braunschweig, Paper 13.01, 1987.
5. **M. Sone and Y. Toriyama,** ”Liquid Crystal Lichtenberg Figure”, J. Appl. Phys. Lett. 24, pp. 115-117, 1974.
6. **I. Gallimberti, G. Marchesi, and L. Niemeyer,** “Streamer Corona at Insulator Surface”, Proc. 5th Int. Symp. on High Voltage Engineering, Dresden, Paper 41.10, 1991.

List of Figures

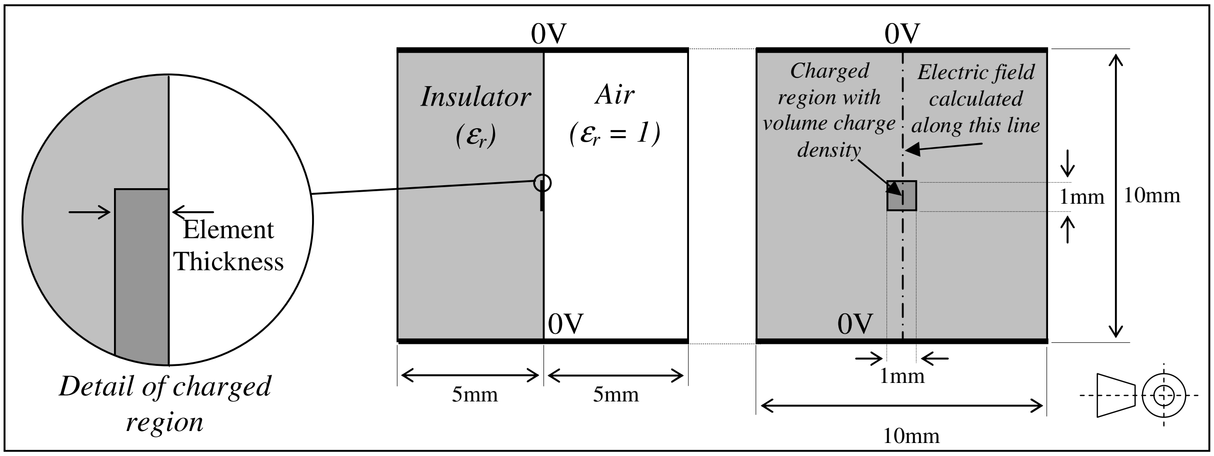

Figure 1: A simple model to study the field produced by a charged region.

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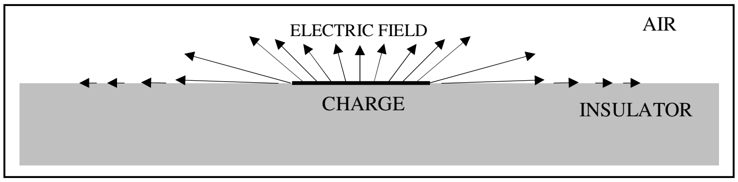

Figure 2: The electric field on the surface of an insulator set up by a uniform region of surface charge.

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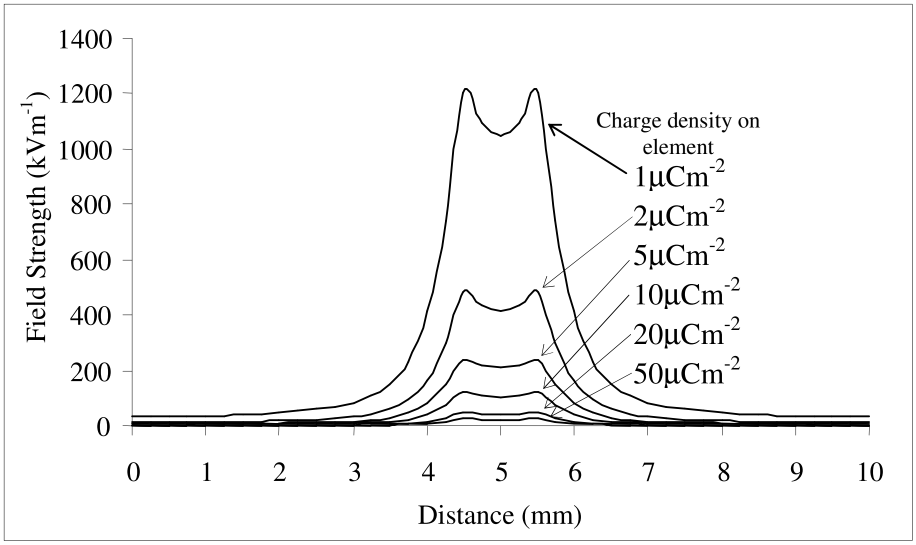

Figure 3: The magnitude of surface electric field strength along a path through the centre of the charged region.

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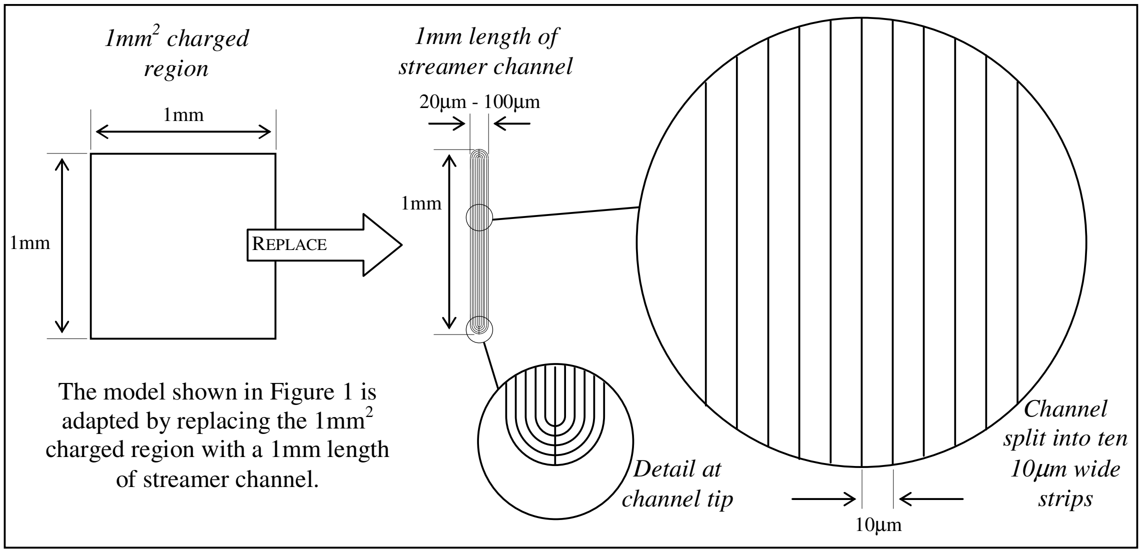

The model shown in Figure 1 is adapted by replacing the 1mm^2 charged region with a 1mm length of streamer channel.

Figure 4: Detail of the model used to simulate different streamer channel widths.

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Streamer channel width	Surface Charge Density required to produce 10pC per mm
1 mm	10 μCm^{-2}
100 μm	100 μCm^{-2}
80 μm	125 μCm^{-2}
60 μm	167 μCm^{-2}
40 μm	250 μCm^{-2}
20 μm	500 μCm^{-2}

Table 1: The uniform charge densities applied to the 1mm length of modelled streamer channel to produce a total positive charge of 10pC for different streamer widths.

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Region	Charge Density	Area	Charge
A	**16 µCm^{-2}**	1mm×10µm	16 fC
B	**44 µCm^{-2}**	1mm×10µm	44 fC
C	**92 µCm^{-2}**	1mm×10µm	92 fC
D	**152 µCm^{-2}**	1mm×10µm	152 fC
E	**196 µCm^{-2}**	1mm×10µm	196 fC
F	**196 µCm^{-2}**	1mm×10µm	196 fC
G	**152 µCm^{-2}**	1mm×10µm	152 fC
H	**92 µCm^{-2}**	1mm×10µm	92 fC
I	**44 µCm^{-2}**	1mm×10µm	44 fC
J	**16 µCm^{-2}**	1mm×10µm	16 fC

TOTAL = 10pC

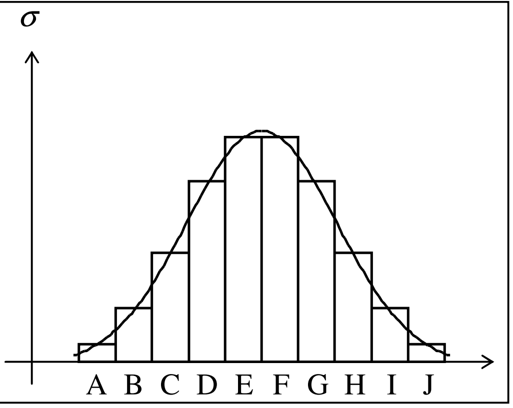

Figure 5: The uniform charge densities applied to each of the streamer channel strips to produce a Discrete-Gaussian distribution of charge with a net charge of 10pC per mm.

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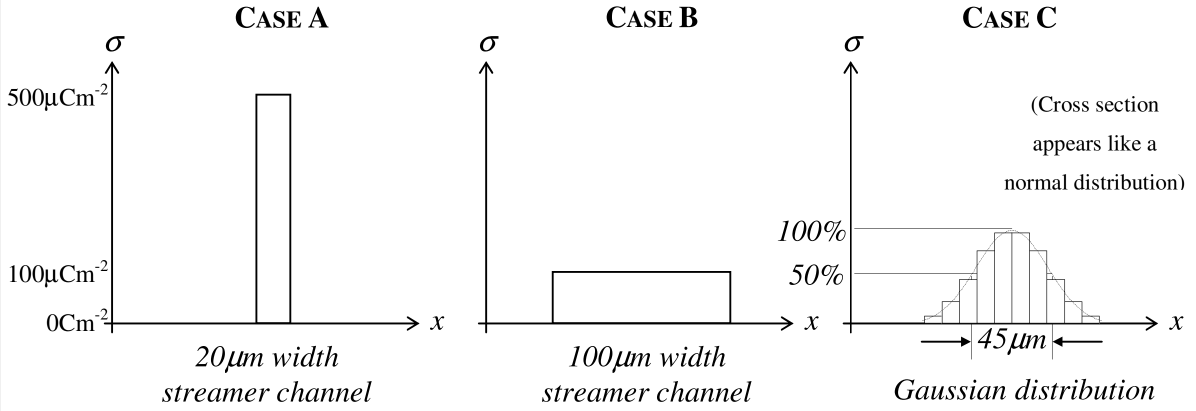
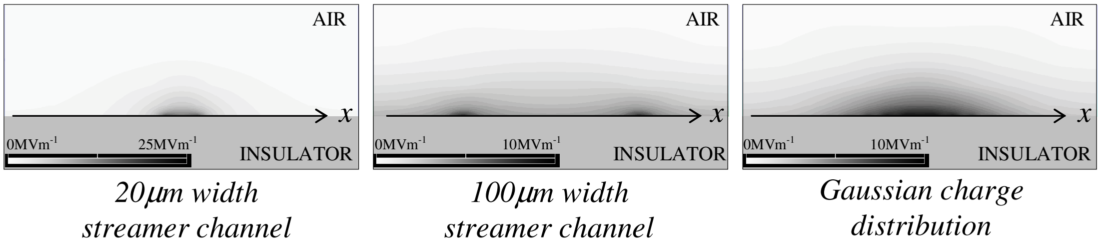
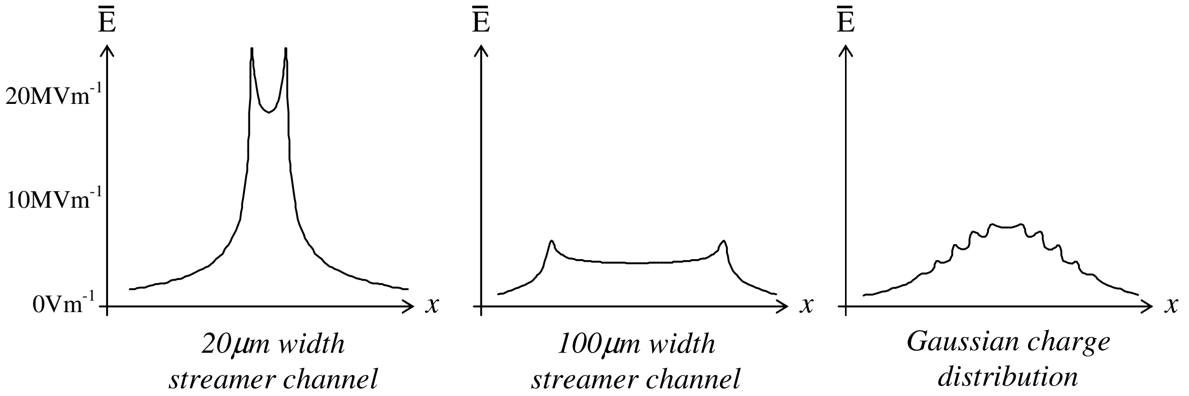


(a) Charge density distribution through cross sections of the modelled streamer channels.



(b) Cross sections through the model showing the electric field in air set up by the surface charge.



(c) The surface electric field strengths through the modelled streamer channel.

Figure 6: The measured value of 10pC of charge per 1mm can result in different electric field strengths depending on how the charge is distributed within the surface element.

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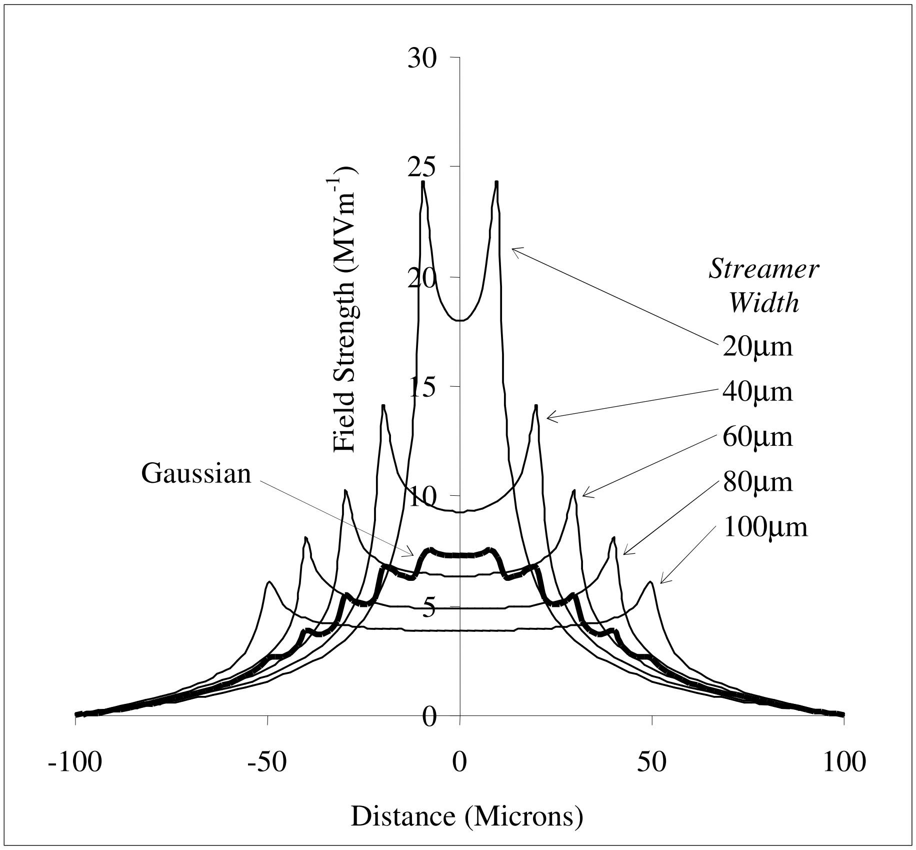

Figure 7: Magnitude of surface electric field strength on surface across the streamer channel for different streamer widths.

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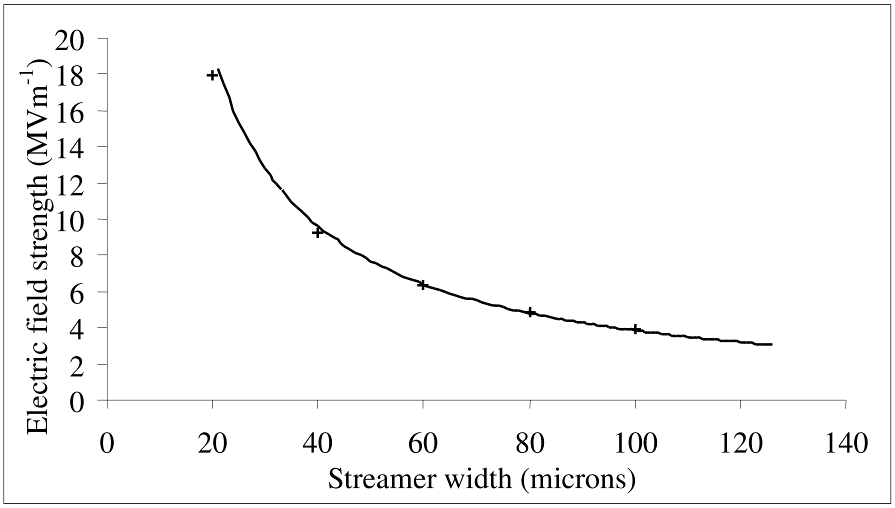

Figure 8: Electric field strength on surface across the streamer channel for different streamer widths.

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