The Electric Field Inside a Gas Cavity Formed at a Solid-Solid Dielectric Interface Stressed with HV Impulse

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Abstract

Interfaces between different solid dielectric materials often exhibit lower breakdown strength when compared to bulk solid materials. Of particular concern in many HV and pulsed-power systems are configurations in which a strong tangential field to an interface is developed. In such cases, past studies [1] have shown that solid-solid interfaces are particularly susceptible to electrical breakdown. A reason for such reduction in dielectric strength is the presence of gas cavities formed at the interface, as a result of the inevitability that the contact surfaces will be rough (**Figure** 1) [2].

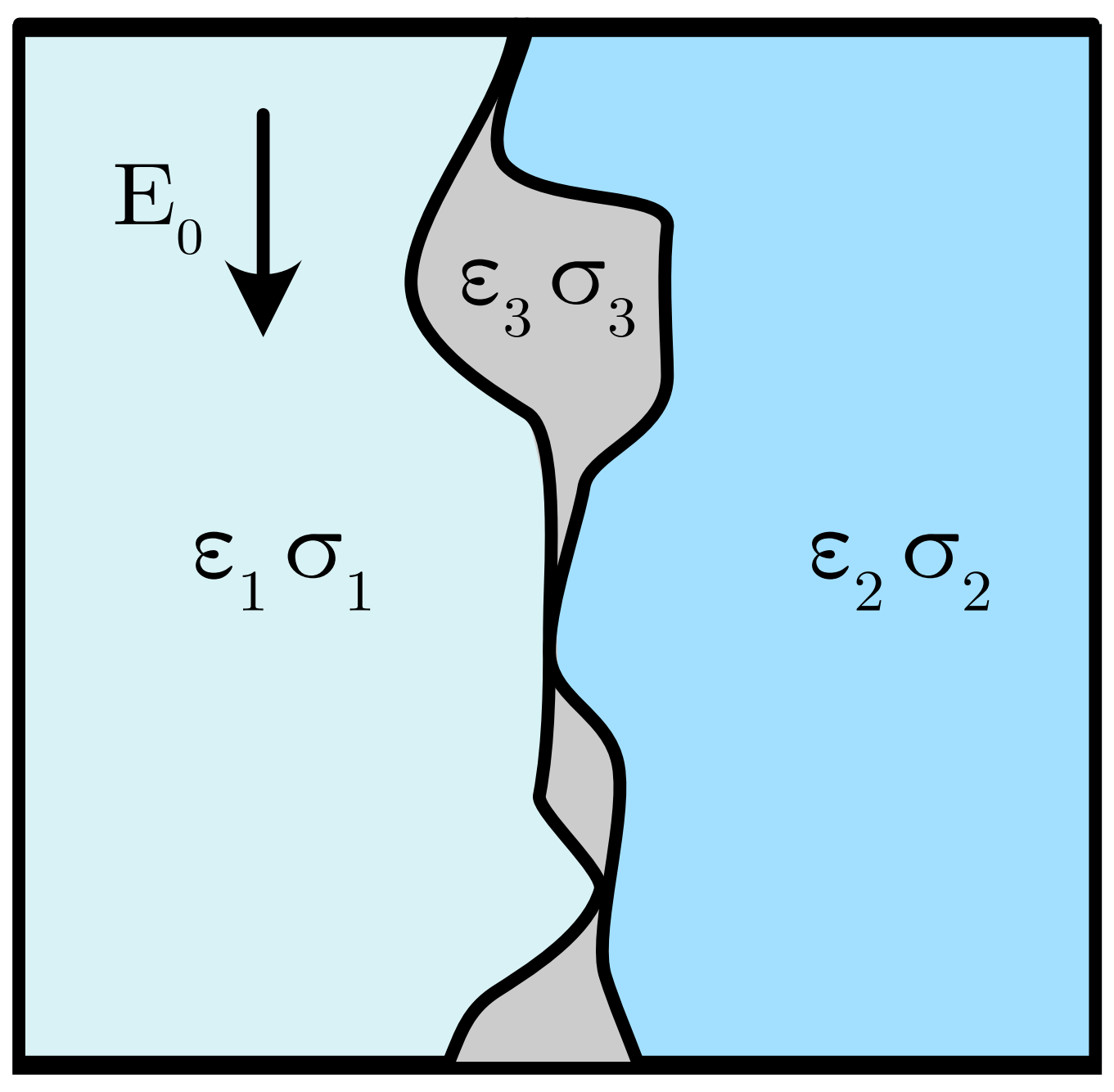

Figure 1: *Emphasised depiction of gas cavities formed at a solid-solid dielectric interface, subject to tangential stress*

If left unchecked, this may ultimately lead to the complete and catastrophic failure of the insulation, severely compromising the integrity of the HV system. While some work, e.g. [3] has been conducted on solid-solid interfaces in steady-state AC regimes, we attempt to extend this knowledge to transient, impulsive energisation and to better include electrical parameters such as permittivity and conductivity into our analysis.

▼ In Summary, we hereby present ▼

The self-consistent solution of the **pre-breakdown Laplacian field** around a **single gas cavity** encased in a **poorly-conductive bulk**.

Two **fully analytical models** for the electric field approximating the cavity as (1) a **spheroid** and (2) an **ellipsoid**, under a **uniform external field** energised with a **double-exponential impulsive waveform.**

The inclusion of an additional layer on the inside of the void as a **model for potentially heightened permittivity and conductivity**, possibly as a result of previous (partial) discharge activity.

Preliminary analysis of the **transient behaviour** and identification of parameters which **may significantly effect the time evolution of the electric field** inside the gaseous cavity.

Mathematical Model

We solve Laplace's Equation (1) for two axisymmetric geometries, utilising spheroidal coordinates (r,θ,Φ) and prolate ellipsoidal coordinates (μ,ν,Φ) as shown in **Figure** 2:

$$\nabla^2\varphi = 0 \tag{1}$$

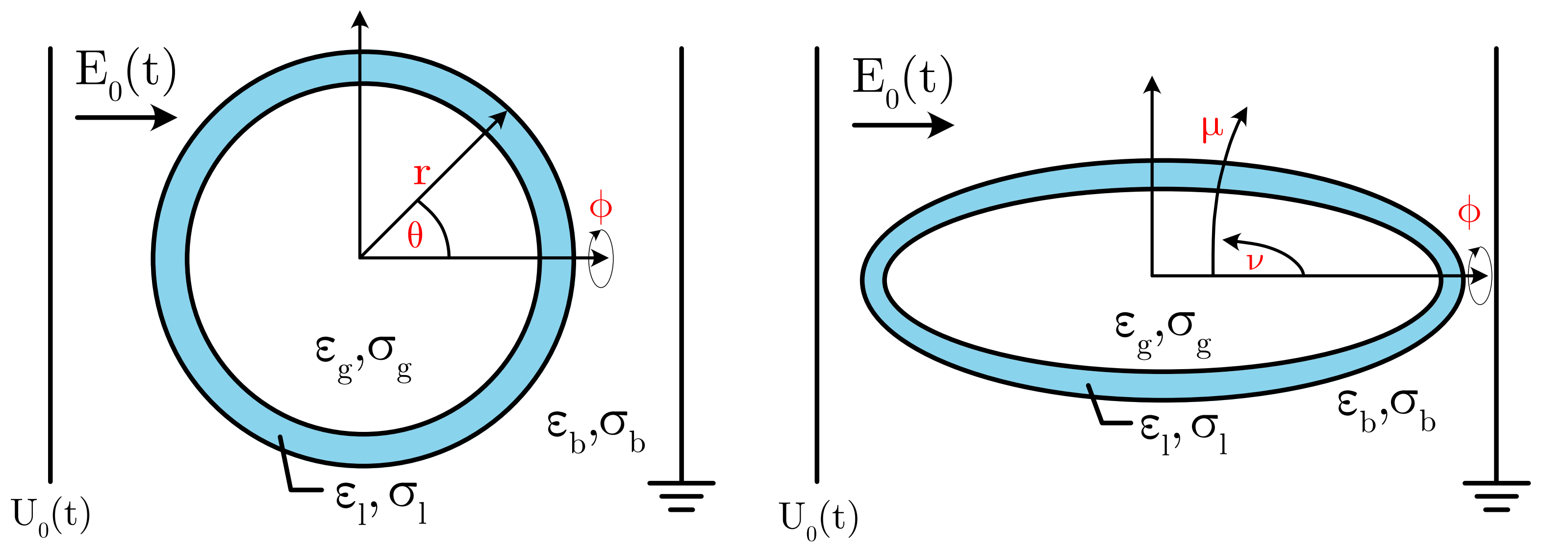

Figure 2: *Domains for the analysis of gas cavities. (Left) Spheroidal coordinate system. (Right) Prolate Ellipsoidal Coordinate system. ε, σ are the relative permittivity and electrical conductivity (S/m) respectively. Subscripts b, l and g refer to the bulk, layer and gas.*

The boundary value problem may be set up by imposing electrostatic boundary conditions across each interface and far from the cavity:

▼ Potential Continuity ▼

$$\varphi_g(\boldsymbol{x_1}) = \varphi_\ell(\boldsymbol{x_1})$$
$$\varphi_b(\boldsymbol{x_2}) = \varphi_\ell(\boldsymbol{x_2})$$
$$\varphi(\mu, r\to\infty) = \varphi_0$$

▼ Normal Flux & Current ▼

$$\boldsymbol{J}_g\cdot\hat{\boldsymbol{n}} + \partial_t\boldsymbol{D}_g\cdot\hat{\boldsymbol{n}}|_{\boldsymbol{x_1}} = \boldsymbol{J}_\ell\cdot\hat{\boldsymbol{n}} + \partial_t\boldsymbol{D}_\ell\cdot\hat{\boldsymbol{n}}|_{\boldsymbol{x_1}}$$
$$\boldsymbol{J}_\ell\cdot\hat{\boldsymbol{n}} + \partial_t\boldsymbol{D}_\ell\cdot\hat{\boldsymbol{n}}|_{\boldsymbol{x_2}} = \boldsymbol{J}_b\cdot\hat{\boldsymbol{n}} + \partial_t\boldsymbol{D}_b\cdot\hat{\boldsymbol{n}}|_{\boldsymbol{x_2}} \tag{2}$$

Here, **x** is the coordinate, where subscript 1, 2 represent the boundaries between g,l and l,b respectively. **J** is the current density and **D** is the electric flux.

The Laplace Transform is applied such that $\partial_t \longrightarrow s$ and the resulting set of linear equations are solved.

Results & Analysis

▼ Field Enhancement ▼

The self consistent solution of the equation (1) with (2) yield expressions for the cavity field of the form:

$$\mathbf{E}_g(r,\theta,t) = A_g(t)_s\left[\sin\theta\ \hat{\boldsymbol{\theta}} - \cos\theta\ \hat{\boldsymbol{r}}\right]$$
$$\mathbf{E}_g(\mu,\nu,t) = \frac{A_g(t)_e}{h_\mu}\left[\sinh\mu\cos\nu\ \hat{\boldsymbol{\mu}} - \cosh\mu\sin\nu\ \hat{\boldsymbol{\nu}}\right] \tag{3}$$

Where coefficients $A_g(t)$ are dependant on all pairs of parameters (ε,σ), geometry, input waveform parameters, and time. Subscripts differentiate between respective cavity shape, **s**pheroid or **e**llipsoid. The full spatially varying fields are able to be visualised from their closed form expressions as shown in **Figure** 3.

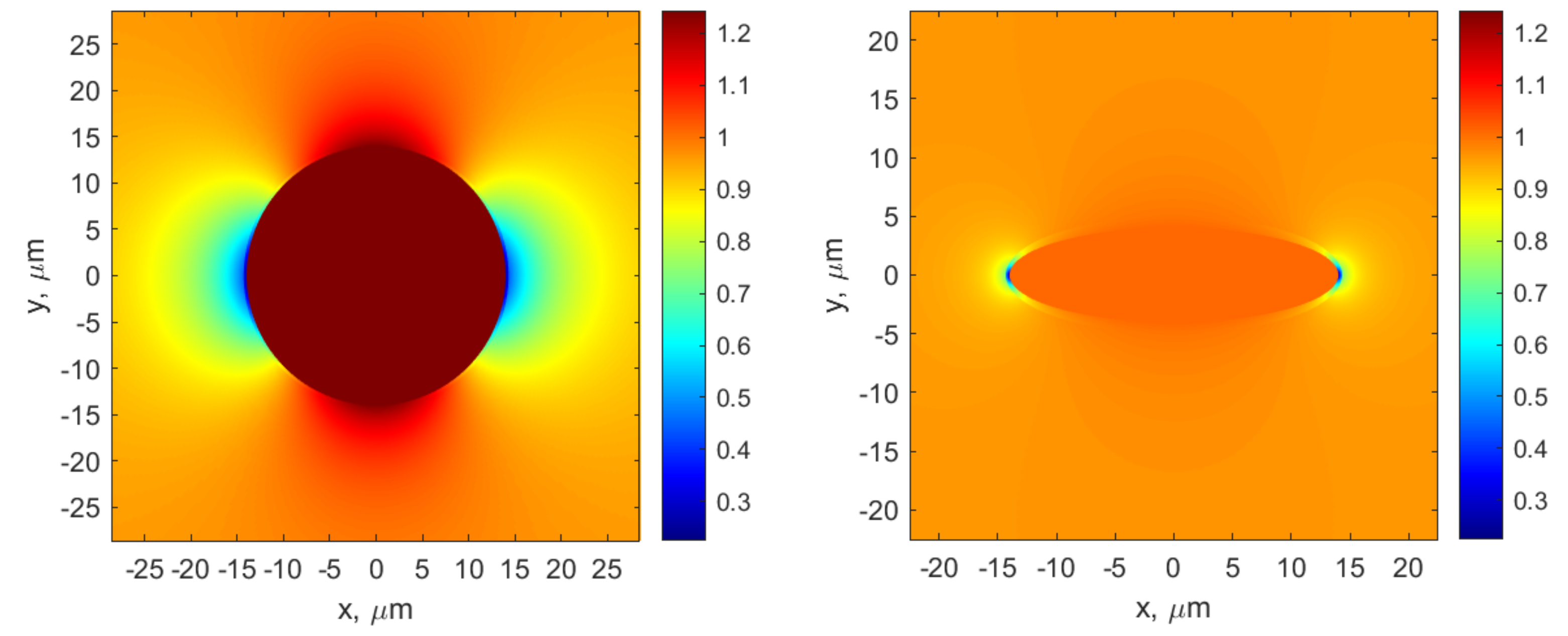

Figure 3: *Colour plots representing the field enhancement E/E_0 in a gas cavity. Parameters (ε,σ) here are $(3.2,10^{-12})$, $(4.5,10^{-9})$ and (1,0) for the bulk, layer and gas respectively. Energising voltage is +5 kV with a gap separation of 4 mm. Cavity dimension parallel to the field is 30 μm with a layer ~1 μm.*

▼ Parametric Analysis of Transient Response ▼

Closed form solutions allows any system parameter to be readily swept across a large range of values. **Figure** 4 encloses the behaviour of the peak cavity electric field strength and peak time as a function of the bulk parameters (ε,σ), whilst the layer parameters are kept constant (as in **Figure** 3). The energising impulse is of the double-exponential form (4) and tuned to give a standard 1.2/50 μs lightning impulse as an example.

$$U_0(t) = A_0 U_0\left(e^{-\alpha t} - e^{-\beta t}\right) \tag{4}$$

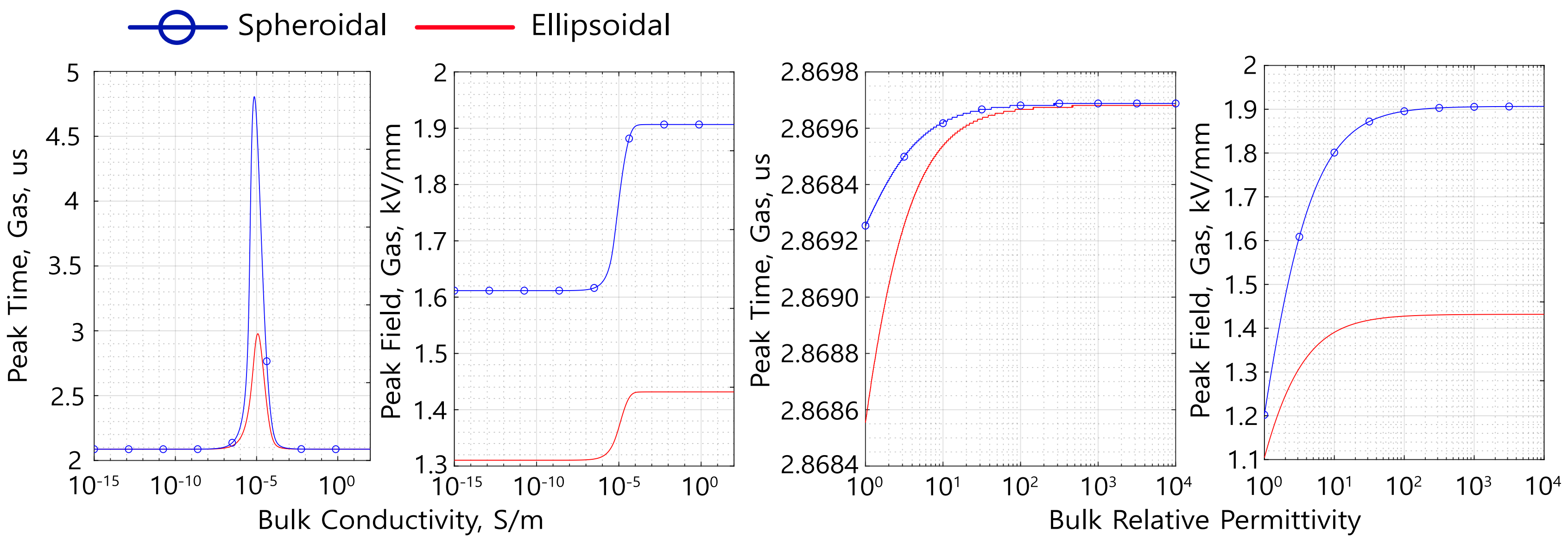

Figure 4: *Plots of the peak field magnitude and peak time inside the gas cavity as a function of bulk conductivity and permittivity. Notice the significant change in peak time for around σ = ~10^{-5} S/m under this configuration. Similar analysis can be repeated for all system parameters.*

Conclusions & Future Work

Fully analytical, closed-form expressions for the electric field inside a cavity at a solid-solid interface have been derived. The model considers **arbitrary (ε,σ)** in the **bulk**, the **cavity** and an **additional layer** introduced as a model for **heightened parameters on the void internal surface.**

Parametric analysis over a large range of material parameters is possible with this model, and was conducted under a **1.2/50 μs lightning impulse signal**.

It is observed that the **transient behaviour** of the field inside the cavity is **complex**, and under certain (ε,σ) the **peak time can increase significantly beyond the peak of the input signal.**

The model is expected to be extended further to include **nonuniform external field** topologies such as **spherical** or **needle electrodes.**

It is planned to use the current model alongside a **kinetic** approach for the **prediction** of solid-solid **interfacial breakdown under impulsive stress.**

References

[1] - R. Ross, "Dealing with interface problems in polymer cable terminations," IEEE Electrical Insulation Magazine, vol. 18, pp. 5-9, 1999.

[2] - E. Kantar, F. Mauseth, E. Ildstad and S. Hvidsten, "Interfacial breakdown between dielectric surfaces determined by gas discharge," in IEEE Conference on Electrical Insulation and Dielectric Phenomenon. IEEE, 2017, pp. 556-559

[3] - E. Kantar, D. Panagiotopoulos and E. Ildstad, "Factors influencing the tangential ac breakdown strength of solid-solid interfaces," IEEE Transactions on Dielectrics and Electrical Insulation, vol. 23, pp. 1778-1788, 6 2016.