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New investigations of the mechanisms of lightning strokes to radomes. Part II : Modeling of the protection efficiency

A. Delannoy, A. Bondiou-Clergerie, P. Lalande, P. Blanchet, P. Laroche
Onera, Chatillon, France

G.L. Bacchiega, I. Gallimberti
IRS, Padova, Italy

ABSTRACT

Experimental studies of the mechanisms of lightning strokes to radome have shown that the protection efficiency can be related to the ability of diverter strips to initiate stable leaders before inception of energetic discharges take place inside the radome. A model based on a 3D code for electric field calculation is used to compute the threshold of these different processes and deduce the optimum strip height for a given internal electrode configuration. The results of this model are successfully compared to experimental estimation of optimum protection.

INTRODUCTION

The mechanisms of inception and propagation of corona and leader discharges around a radome, equipped with 4 diverter strips and an internal electrode representing the radar, are described in a companion paper [1]. The radome is located in a plane to plane gap submitted to an impulse voltage. The objective of the present study is to build simplified modeling of the observed processes in order to identify the parameters for an optimal protection of the radome. We first present a quantitative analysis of the different discharge regimes observed in low ambient humidity. The second part of the paper is devoted to the calculation of physical thresholds for inception of these discharges, these thresholds being used to determine the optimum diverter strip height.

PHYSICAL PROCESSES OBSERVED IN LOW AMBIANT AIR HUMIDITY

DISCHARGES FROM DIVERTER STRIPS

At low ambient air humidity, the radome is perfectly insulating. Therefore, the field measured at the internal electrode [1] is lowered only by the presence of the diverter strips through three different effects that appear in sequence during the voltage rise:

- Geometric effect
- Space charge effects associated with the corona emitted by the diverter strips
- Leader channel effects acting as an extension of the strip

If the maximum E-field is obtained at the strip - rather than inside the radome - one or several coronas will develop from that point, followed by the propagation of a leader. Figure 1 gives a streak picture of the different discharges regimes that follow one another at the tip of a diverter strip

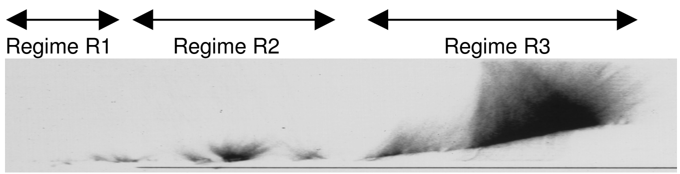

Figure 1 : Different discharges regimes initiated at the tip of the strips (streak photograph ; total duration 100µs; voltage rise time 130µs)

<u>R1 regime: weak coronas</u>

This low voltage regime (around 100kV) is associated with numerous very weak coronas whose charge is lower than 0.1 µC, with an extension around 1cm (figure 2). This regime is typical of very low curvature radii electrodes. It is necessary to take into account the corresponding total space charge which locally distorts the electric field and modify the trajectory of subsequent discharges. In fact, it can be seen on the streak pictures that the coronas and leaders of regimes R2 and R3 do not develop on the radome surface but perpendicularly to the strip axis.

<u>R2 regime : coronas and unstable leaders</u>

When the applied voltage is high enough, more energetic discharges are initiated and deposit space charge higher than 0.1 µC. Careful analysis of the shape of the corresponding current pulses show that these coronas are associated with an unstable very short leader (or "stem") : this leader is poorly conductive and cannot propagate over distances larger than a few cm. Figure 3 presents the corona/stem charge as function of the applied voltage. The measurements follow a classical law Q=k.V.(V-Vs) where Vs is the voltage threshold for regime R2, very similar to previous observations in point to plane gaps. The voltage threshold decreases as the strips height increases.

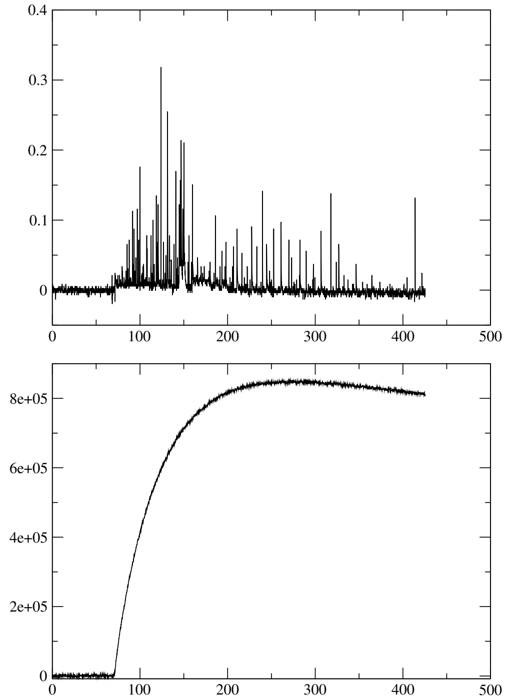

Figure 2 : Weak corona regime: current measured at one of the diverter strip together with the voltage waveform.

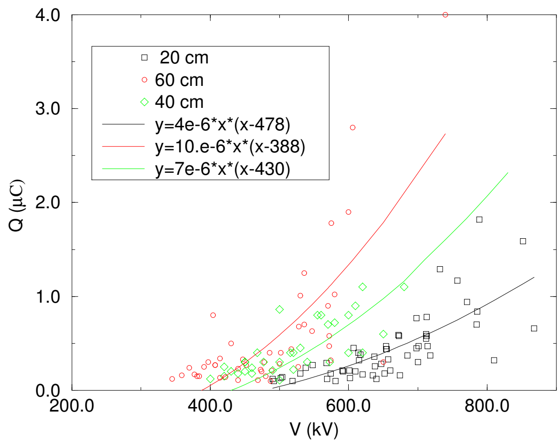

Figure 3 : Corona/stem regime: charge as function of applied voltage for 3 strip heights (20, 40 et 60 cm)

<u>R3 regime : stable leader</u>

For an higher applied voltage, one of the stems may become an actual stable leader and propagates up to the high voltage plane, carrying a slowly varying current between 0.5 A and 1A (figure 4). The distribution of the inception voltages for different strip heights is given in figure 5

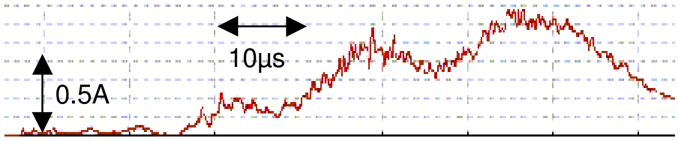

Figure 4 : Current associated with a stable leader originating from one of the diverter strips

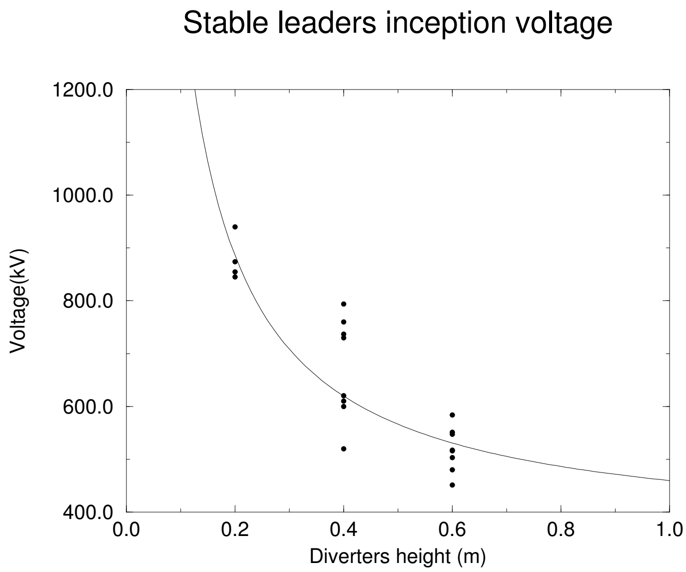

Figure 5 : Stable leader inception voltages as function of diverter strip height

DISCHARGE FROM INTERNAL ELECTRODE

Discharges from the internal electrode have been observed only with small diverter strips (height H≤20cm). Current measurements at the electrode indicate that the first corona is followed by a leader, whose propagation is arrested at the internal radome surface. The total charge associated with the corona-leader system is around 8µC, independently of the applied voltage because of the leader length limit. Figure 6 gives the voltage, current, and E-field measurements associated with such an internal discharge (diverter strips height=20cm). In this case, corona and leader discharges have finally been initiated from a diverter strip leading to breakdown without radome puncture.

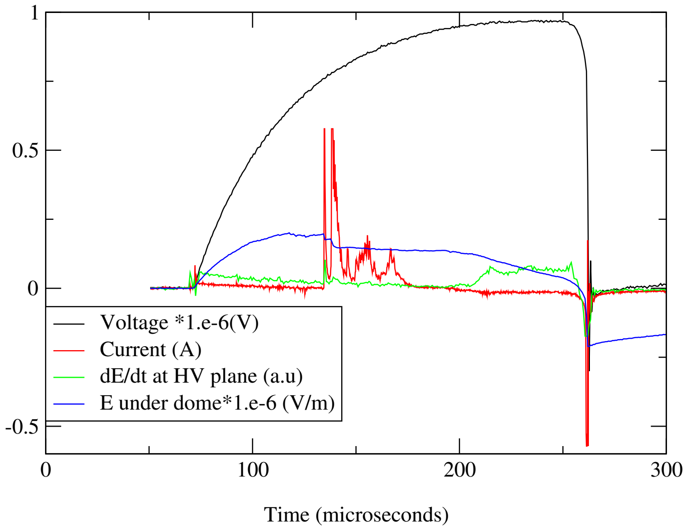

Figure 6 : Measurements associated with the inception of a discharge from the internal electrode.

CONDITIONS FOR DIELECTRIC PUNCTURE

In some cases, the inception and development of an internal discharge is followed by a final breakdown though a puncture of the radome material. It can be observed that, in the last few µs before breakdown, the fields measured inside the dome and at the HV plane both increase (see figure 7 at time t=362 µs). This is consistent with the inception of a bipolar discharge from the tip of the radome (see the scheme on figure 8) similar to the one observed under high ambient air humidity conditions [1]

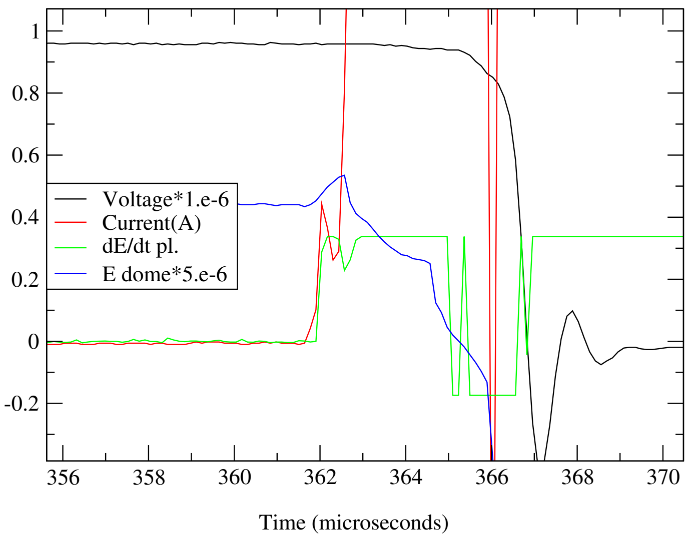

Figure 7 : Measurements of voltage, current and fields prior to the final breakdown in case of a radome puncture

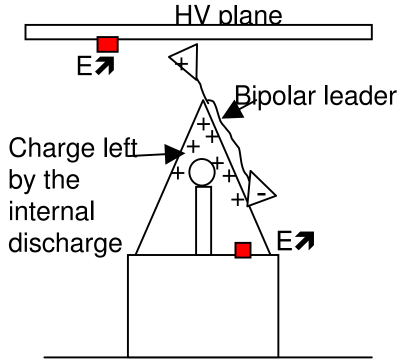

Figure 8 : Scheme of the bipolar leader development.

Conditions for inception of a bipolar leader at the radome tip are reached because the geometric field is increased by the effect of space charge deposited inside the radome by the previous internal discharge. The bipolar leader development causes the measured field to rise both at the negative HV plane (because of the ascending positive part) and under the dome (because of the descending negative part). The electric field in the dielectric material is increased by the combined effect of internal charge and negative leader propagation. This finally results in the dielectric puncture and breakdown. This hypothesis is confirmed by the calculation of E-field at the tip of the radome considering a 8µC charge deposited on its internal face : it results above 2.5 MV/m, almost sufficient to cause air breakdown (figure 9)

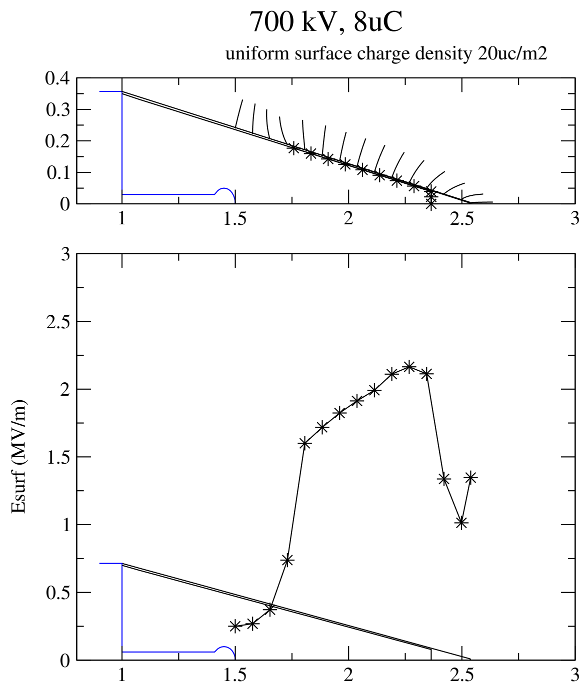

Figure 9 : Top :Representation of field lines starting from the radome surface with 8µC uniformly deposited on its internal surface (Applied voltage 700 kV) Bottom: calculation of E field along the radome (in MV/m).

BASIC PRINCIPLES FOR MODELING OPTIMUM PROTECTION DEVICES

The general purpose of this section is to determine the minimum ambient field (or applied voltage in a plane-to-plane configuration) leading to the development of a stable leader from one of the diverter strips. This threshold field has to be lower than the threshold field for an internal discharge, because any internal discharge may lead to radome puncture through the development of a bipolar leader from the radome tip. For a given number of strips, the optimum height is then determined according to the principles indicated on figure 10.

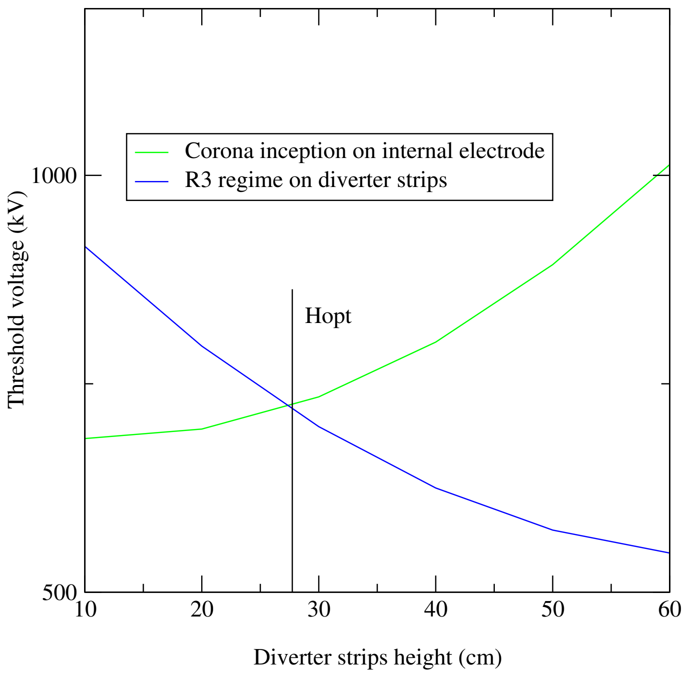

Figure 10 : Principle of determination of optimum protection height in a given electrode configuration

The model relies upon 3D field calculation using a numerical solution of the Poisson field equation. This code – based on a classical integral method – enables to take into account the presence of dielectric materials, space charges and linear conductors. The calculation of physical thresholds for inception of coronas and stable leaders is based on published models of the positive discharge development [2][3][4].

PHYSICAL BASIS

The ambient field threshold (or minimum applied voltage in a plane to plane configuration) for corona inception at a given electrode can be calculated through the following criteria

$$\exp\left(\int_{\Delta z}(\alpha-\eta)dz\right) \geq N_{crit} \approx 10^8 \quad \text{(Eq.1)}$$

Δz is the length of the region around the electrode where the electric field is greater than critical air breakdown field. α and η are the ionization and attachment coefficients depending of the local field value calculated with the Poisson code. Eq.1 evaluates the minimum number of electrons produced by an avalanche near the electrode; this number must be large enough to ensure the local field to be able to produce another avalanche at least of the same size[5].

The calculation of the charge Q associated with the development of a corona in a given voltage distribution $U_1(x)$ can be obtained by the following equation :

$$Q = K.4\pi\varepsilon_0.\int_a^b \left[U2(x) - U1(x)\right]dx \quad \text{(Eq.2)}$$

where $U_2(x)$ is the voltage distribution after corona complete extension and K is a geometric factor describing the average shape and position of corona filaments [4]. It has been shown, in more complex models, that the field in the corona region is almost constant, around 5. kV/cm under positive polarity and 7.5 kV/cm under negative polarity [3]. This property of corona discharges and the calculation of their charge Q are illustrated in figure 11.

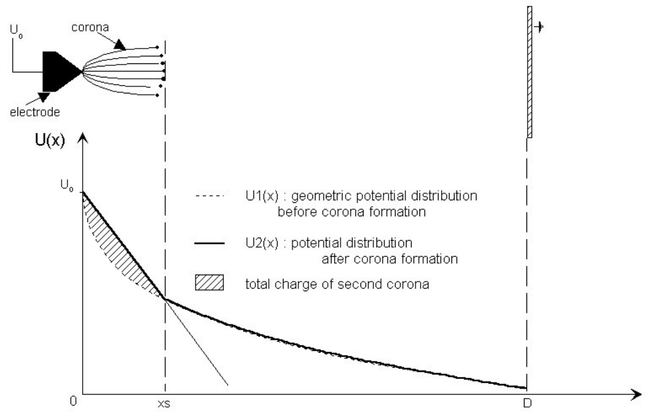

Figure 11 : Potential distributions in a rod-plane gap at corona inception (from [4])

By using this simple model, it is possible to compute the corona charges for different applied voltages and for different diverter heights (figure 12). The calculation is performed along a field line perpendicular to the strip in order to take into account the presence of previous space charge left by the coronas of regime R1. The calculation is in very good agreement with the measurements reported on figure 3

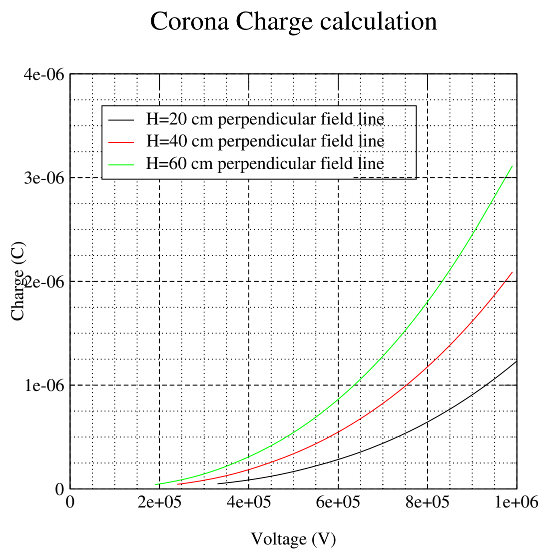

Figure 12 : Calculation of corona charges produced at the top of the strips, as function of the potential applied to the HV plane, for different strip heights.

The current injected from the corona region into the leader channel induces Joule heating of the gas in front of its head. As a critical temperature T_{crit} is reached, the conductivity greatly increases due to the thermal detachment of negative ions [2]. The leader head appears as a propagating thermal transition wave, which converts the cold diffuse glow of the corona into a hot filamentary channel.

The condition for inception of a stable conductive leader can be obtained from the energy balance at the corona root [2]:

$$\frac{d}{dt}\left(\frac{7}{2}k\pi a^2 n_h T_h\right) = (f_r + f_t + f_e)E.I \quad \text{(Eq.3)}$$

where fr, ft, et fe are the fractional input in the various forms of internal energy (rotation, translation and electron excitation) ; E is the field in the corona region ; I is the current injected by the corona

Assuming that the gas heating occurs at constant mass ($n_h \pi a^2 = cstte$) the minimum charge necessary to reach the critical temperature T_{crit} is given by the following equation :

$$Q = \frac{7}{2}\frac{k\pi a_0^2 n_{h0} (T_{crit} - T_0)}{E.(f_r + f_t + f_e)} \quad \text{(Eq.4)}$$

T_{crit} = 1500K (critical temperature for thermal detachment of negative ions); T_0, n_{h0} :temperature and density of ambient air ; a_0 : initial radius of corona filaments (a_0=100µm); ft+fr+fe =0.13 [2]

Under these assumptions, the minimum charge necessary to create a conductive leader is around 0.8µC. For H=20,40 and 60 cm , figures 3 and 12 indicate that this critical charge corresponds respectively to threshold potentials equal to 900 kV, 600 kV and 520 kV. These potentials are consistent with the experimental results given on figure 5: this indicates that the value of 0.8 µC as a critical charge for leader inception is correct.

Eq.1 is used to compute the potential threshold for inception of regime R2 while Eq.2 and Eq.4 are used to compute the voltage necessary for creation of a critical charge of 0.8 µC. The computation has been performed as function of the diverter strips height (figure 13).

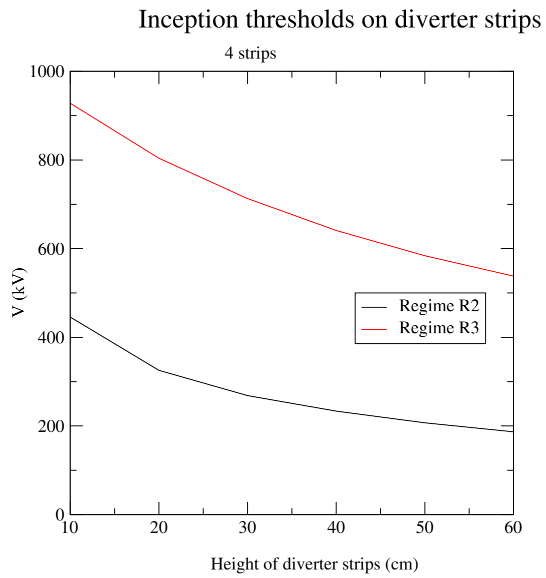

Figure 13 : Computation of voltage threshold for the different discharge regimes initiated from the strips

The threshold for corona inception at the internal electrode is calculated using Eq.1. The calculation of local field at the tip of the electrode is performed taking into account the presence of coronas at the tip of each diverter strips, adding a space charge component to the geometric field (figure 14)

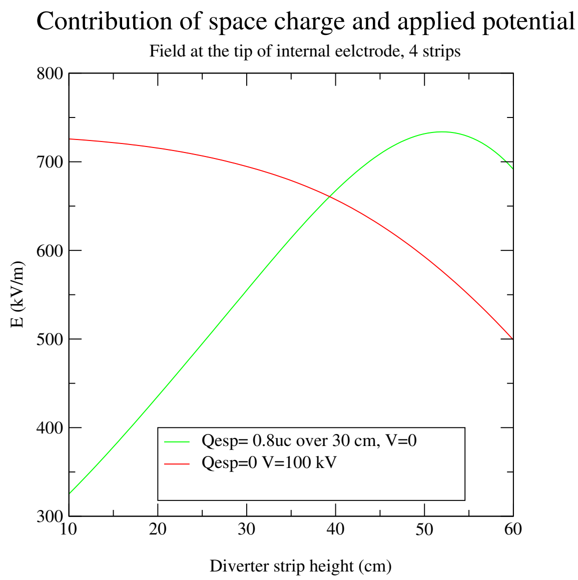

Figure 14 : Field calculation at internal electrode

RESULTS

Based on these principles it is possible to compute the optimum strip height as indicated on figure 15 where we have plotted the threshold voltage for corona inception inside the dome using data displayed on figure 14. :

$$E_{inc} = \frac{E_g}{100} \times V_{inc}(kV) + E_q \quad \text{(Eq.5)}$$

- E_q is calculated including a space charge component corresponding to 0.8 µC at the strips tip
- E_g is calculated without any space charge (geometric component with V=100kV)

The optimum height is found to be around 30cm : this is consistent with the reported experimental results (no internal discharge observed for H=40cm, internal discharges in 50% of the cases for H=20cm).

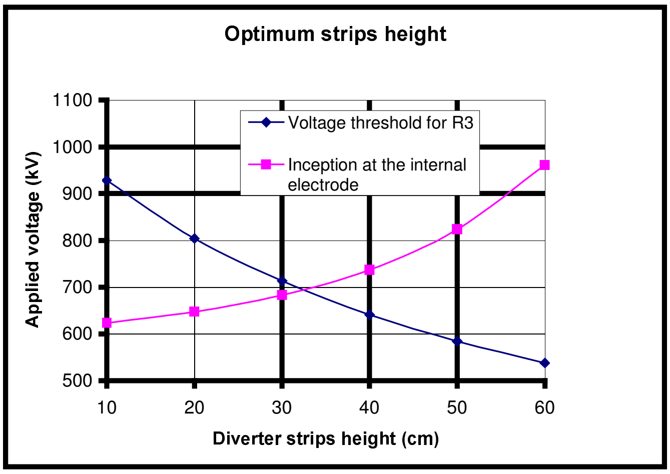

Figure 15 : Calculation of optimum height for 4 strips

The same type of calculation can be done for different number of diverter strips, keeping the same central electrode (see table1).

Numbre of diverter strips	2	4	8
H_{opt}	36 cm	32 cm	28 cm

Table1

The influence of internal electrode height (keeping the same shape and tip curvature radius) is analyzed though the calculations reported on figure 16. The results are summarized in table2

Electrode height	130 cm	140 cm	150 cm	160cm
H_{opt}	14 cm	23 cm	32 cm	41 cm

Table 2

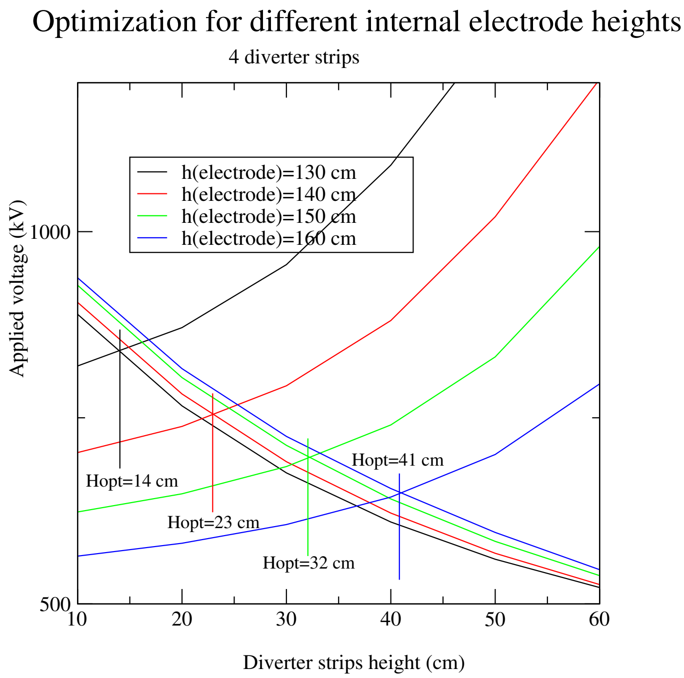

Figure 16 : Calculation of optimum strip height for different internal electrode height (4 diverter strips)

CONCLUSION

The simple model presented here allows to determine the minimum strips height that ensures avoidance of radome puncture. The results are in very good agreement with experimental determination of optimum height. However, the model is actually based on an electrostatic field computation code which accepts only perfect conductors and insulators. It has been shown in a companion paper [1] that, in the case of high ambient humidity, fiber glass radomes may become partially conductive and play an active role in the discharge inception. It would also be interesting to define optimum heights in the case of segmented strips whose conductivity is highly non linear. The extension of the model to such cases implies the use a different code for E-field calculation based on temporal or spectral resolution of the Maxwell equations; however, the physical basis of the model would remain very similar.

ACKNOWLEDGMENTS

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