

**BACK-CORONA MODEL FOR PREDICTION OF ESP EFFICIENCY
AND VOLTAGE-CURRENT CHARACTERISTICS.**

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ABSTRACT

The back-corona discharge is formed by a series of micro-discharges in the air spaces between the particles of the dust layer deposited on the collecting plates. It starts when the particle resistivity is quite high: it changes the voltage-current characteristics of the electrostatic precipitator and significantly lowers its efficiency.

In the present work, the variation of the voltage-current characteristics, depending on resistivity and particle layer thickness, has been successfully reproduced by a simple electrical circuit model of the dust layer, including a back-corona current generator and the voltage drop across the particle layer.

The model also includes an estimation of the variation of the captation efficiency: as back-corona lowers the ion space charge, the computation of the back-corona current allows to evaluate the variation of the particle charging rate and therefore of their migration velocity.

1. INTRODUCTION

The back corona discharge is a complex non-linear phenomenon, which has been the subject of a limited number of investigations [1-9]; its characteristics and effects are often described only on qualitative basis. Its presence inside of an electrostatic precipitator is usually associated to a threshold in the resistivity of the particle layer deposited on the plates. It is experimentally evidenced by a strong bend in the voltage-current characteristics.

Previous mathematical models of back-corona inside the precipitator duct computed the voltage-current characteristics without taking into account the particle layer resistivity and voltage drop; they were based on a finite difference [10] or finite element [11] simulation of the glow-corona discharge, including the back-discharge ion production associated to the glow corona current density.

This paper describes a simple back-corona model describing the non-linear effects of layer resistivity and thickness. The model highlights the coupling between glow-corona and back-corona, and layer resistivity and thickness.

Back corona inception threshold is linked to the average electric field in the particle layer, and it results one order of magnitude lower than the dielectric particle layer breakdown threshold [1][6].

The value of the back-corona discharge current is defined on the basis of the overvoltage with respect to the inception electric field. Using this value in an equivalent electrical circuit of the dust layer, it has been possible to reproduce the change in the voltage-current characteristics induced by back-corona.

The influence of the positively charged ions produced by back-corona on precipitation efficiency has been estimated through the reduction of the particle charging rate. Finally, using the modified voltage-current characteristics into an iterative method that takes into account the reciprocal influence between efficiency, particle layer thickness and electrical conditions, it has been possible to estimate the efficiency loss created by back-corona. The model results successfully reproduce the efficiency losses described in literature [1][8].

2. BACK-CORONA DISCHARGE MODEL

In a typical electrostatic precipitator configuration a negative applied voltage U_a between an emitter electrode and a collecting plate produce a negative glow-corona discharge at the emitter electrode (Fig.1). The negative ions exiting the glow corona discharge together with the charged particles drift towards the collecting plate.

If the glow-corona discharge current and layer resistivity are high enough, a positive back-corona discharge is formed in the layer. From the dust layer positive ions exit the back-corona discharge and drift towards the emitter electrode discharging previously charged negative dust particles. Besides positive ions may attach to neutral dust particles, causing their drift backwards to the emitting electrodes.

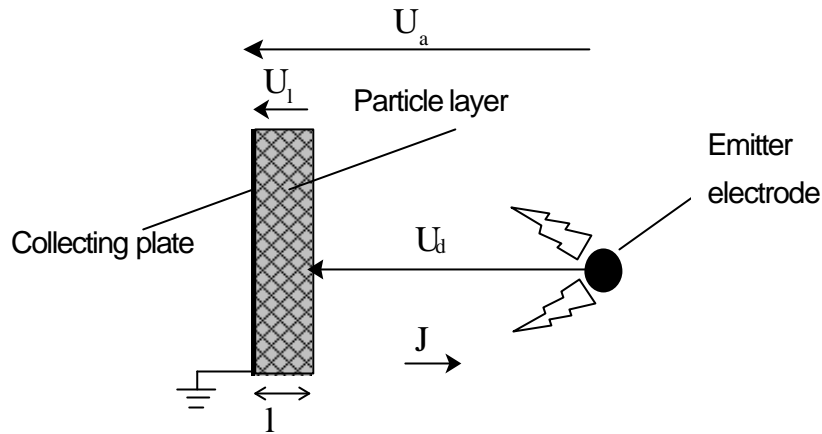


Fig.1 Typical electrostatic precipitator configuration

2.1 Back-corona inception level

The back-corona discharge is formed by a series of micro-discharges in the air spaces between the dust particles deposited on the collecting plates. It forms when an excessive electric field is induced in the dust layer by the current flowing through its surface. A micro-discharge is associated to the collapse of the void spaces between the deposited particles (Fig.2).

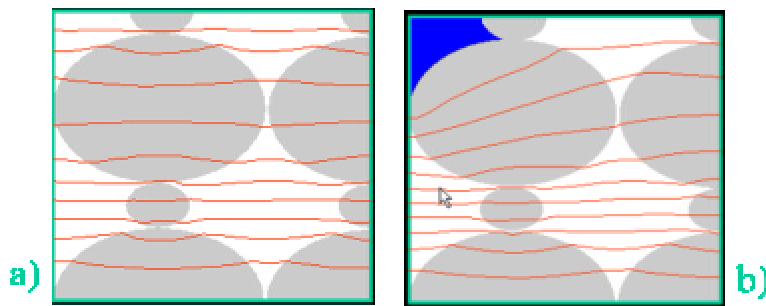


Fig.2 Schematic representation of the equipotential lines within the collected dust layer, before (a) and after (b) the discharge in void spaces

The electric field threshold E_t for back-corona inception depends on different parameters, including particle geometrical shape and compactness inside the dust layer. Its value is very difficult to be measured, as particle layer condition and resistivity inside an electrostatic precipitator are strongly variable.

It is important to point out that the electric field for back-corona inception is not the dielectric breakdown field of the layer, whose value is around $1-2 \cdot 10^6$ V/m [1][6], near the dielectric breakdown of air (about $2.6 \cdot 10^6$ V/m).

In order to quantify the threshold value, the average electric field in the layer E_l can be calculated, as the product of the layer resistivity r and current density J on the collecting plates:

$$E_l = rJ \quad (\text{Eq.1})$$

In the literature there are no published values of the average electric field threshold E_t ; however, a layer threshold resistivity of about $2 \cdot 10^{10}$ Ohm.cm is commonly indicated. By assuming an average current density on the collecting plates around 2.5 - 5.0 mA/m², it is possible to define an electric field threshold of the order of 0.5 - 1 10^5 V/m. This value is confirmed by model theoretical approximations [12] and by the results described hereafter.

2.2 Back-corona current density

The estimation of the back-corona current density J_b is based on the electric field in the particle layer E_l . A typical quadratic relationship has been assumed, corrected for the particle layer thickness l :

$$J_b = k_b l^{0.4} (E_l - E_t)^2 \quad (\text{Eq.2})$$

The value of the constant k_b ($3 \cdot 10^{-6}$) as well as the value of the power of the particle layer thickness (0.4), have been optimized on the basis of SRI resistivity probe measurements and on the laboratory and industrial measurements described in the next chapter.

This current calculation has been kept as simple as possible; it describes the steady state regime, and does not take into account the dynamic behavior of back-corona [5][10].

2.3 Voltage current characteristics

Modeling voltage current characteristics in an electrostatic precipitator with back-corona needs a representation of the particle layer. Particle layer is characterized by his electrical resistivity. From an electrical point of view how the back-corona discharge interact with particle layer resistivity? In our model, back-corona current adds the current produced by the negative glow-corona discharge and do participate to the voltage drop in the particle layer.

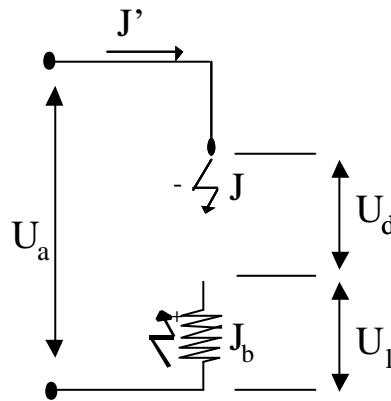


Fig.3 Electrical circuit model describing voltage current characteristics with back-corona

The increased voltage drop creates a higher electric field that increases back-corona current density and once more modifies the voltage drop. We have a positive feedback effect that is a typical phenomenon observed in the presence of back-corona.

It is possible to identify the voltage-current electrostatic precipitator working point including the positive feedback using the equations presented in the previous chapter, where the

function $J(U_d)$ is the voltage-current characteristics without the particle layer and back-corona (see Fig.3 and Eq.3).

$$\begin{cases} J' = J(U_d) + J_b \\ E_l = r J' \\ U_a = U_d + E_l l \end{cases} \quad (\text{Eq.3})$$

The computed influence of particle layer resistivity on the voltage-current characteristics are shown in Fig. 4, for a defined particle layer thickness l of 0.01 cm and using a function $J(U_d)$ taken by the Laboratory ESP described in [5]. The resistivity value does have a great influence on voltage-current characteristics.

The characteristics for low dust resistivity are virtually identical with that obtained with clean plate. As the resistivity value increase the current value increase too. The current rise can be so high that it limits the achievable applied voltage and for high resistivity values voltage-current characteristics go from inception to spark with a variation of the applied voltage of a few kilovolts.

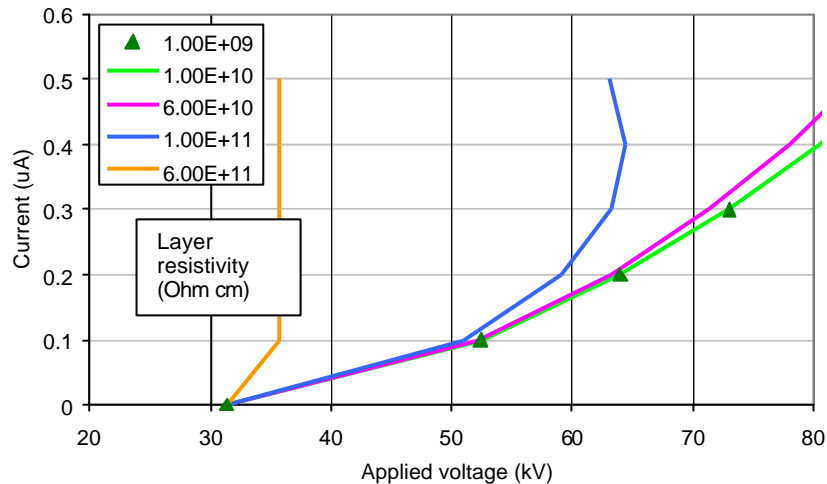


Fig. 4 Voltage-current characteristics as functions of layer resistivity

Back-corona current varies also as function of particle layer thickness. Fig.5 shows voltage-current characteristics with different layer thickness using the same configuration of Fig.4 and 6×10^{10} Ohm.cm layer resistivity. As particle layer thickness increase the back-corona current is higher. The increase of air spaces within the collected dust layer subject to back-corona explains this phenomenon.

Current increase as function of particle layer thickness has been validated on experimental data presented in [5], and shown in Fig.5.

Using this model inside a Electrostatic Precipitator modeling software ORCHIDEE 2 [11] we were able to successfully represent voltage-current characteristics variation as function of dust layer thickness and properties in an industrial environment. The presented model agrees with experimental back-corona available data and well represents qualitative back-corona effects.

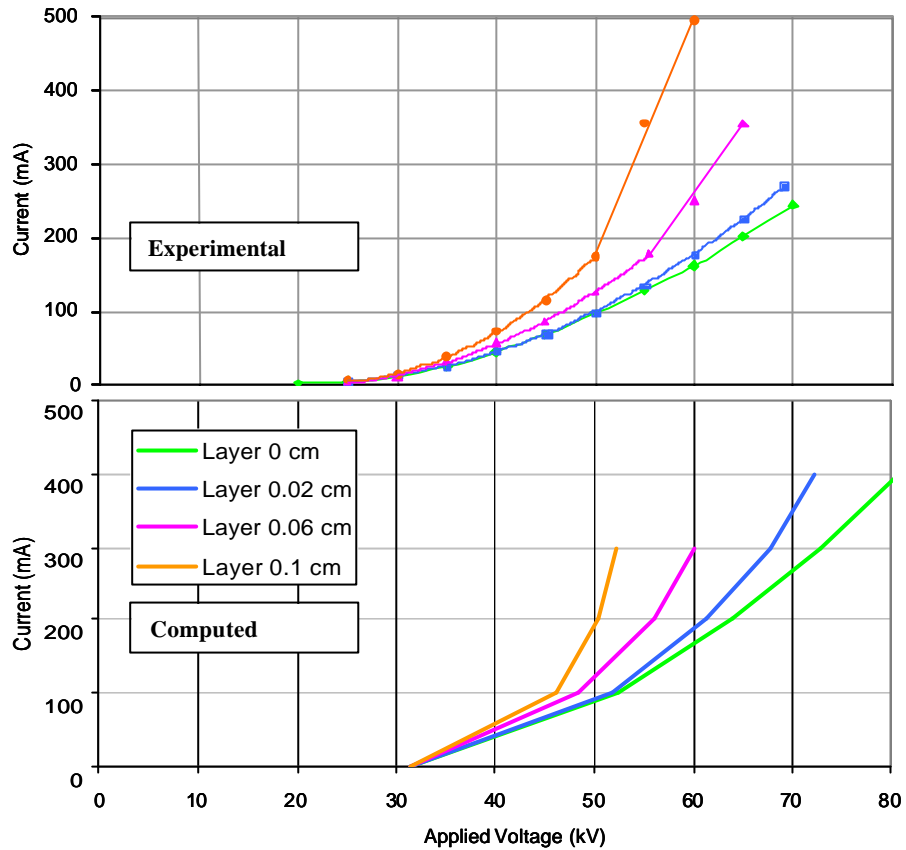


Fig. 5 Comparison between computed and experimental Voltage-Current characteristics, as functions of particle layer thickness

2.4 Graphical representation of the voltage current working point

It is possible to have a graphical representation and solution of the voltage current working point. Rewriting model equations (Eq.3) as shown in (Eq.4), it is possible to show graphically how the applied voltage (U_a) cannot be applied if there is a strong back-corona and how two equilibrium voltages can be associated to given current density.

$$\begin{cases} J_3 = J_1 + J_b \\ J_2 = \frac{\mathbf{r} \, l}{U_l} \end{cases} \quad \text{where } J_1 = J(U_a - U_l) \quad (\text{Eq.4})$$

Fig.6 shows the relationship between voltage drop in the particle layer (U_l , x-axe) and the current density (J , y-axe) of each equation. Voltage drop and current density are computed for a typical configuration, using a standard quadratic $J(U_d)$ function and for a given fixed applied voltage U_a (35 kV).

Curve 1 point up the glow-corona current density variation J_1 . For a given applied voltage and in the absence of back-corona the glow-corona current density lowers as the voltage drop increase.

Curve 2 shows the voltage-current density characteristics given by the particle layer resistivity. The linear curve slope is function of the particle layer resistivity: the higher the slope, the lower the resistivity.

The crossing point of curve 1 and 2 is the electrostatic precipitator working point and fix the voltage drop in the layer. We can imagine graphically how a resistivity variation (i.e. a different slope in curve 2) influences the electrostatic precipitator electrical conditions.

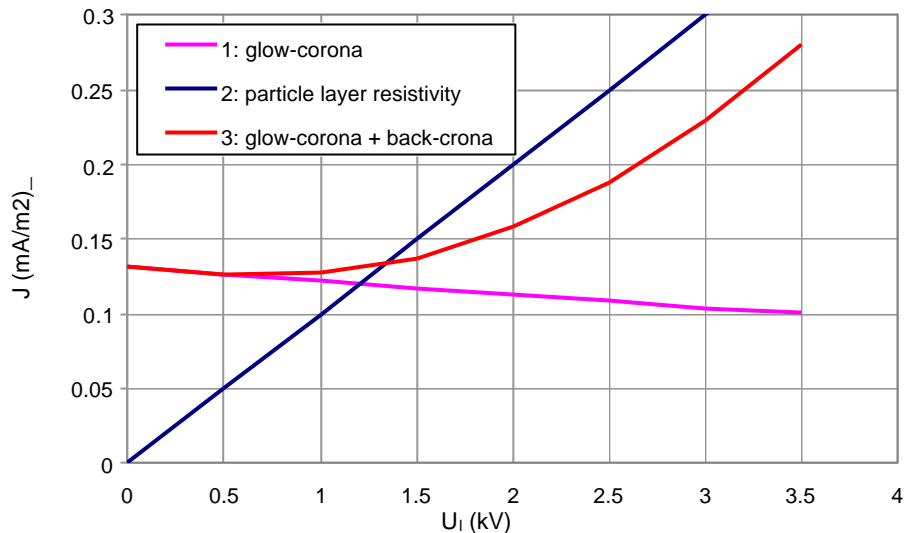


Fig.6 Graphical representation of the voltage current working point

If we add the current density produced by the back-corona to the curve 1 it becomes curve 3 (Eq.4). For a low voltage drop in the layer the back-corona is not incepted and current the current density is null, as the voltage creates a higher electric field in the layer the back-corona current density increase as a quadratic function of U_l .

The crossing point of curve 2 and 3 shows the electrostatic precipitator working point. If we extrapolate the curves we can see that there is actually two crossing point of curve 2 and 3 corresponding to two possible working points in the electrostatic precipitator.

If the back-corona current is high it is actually possible that no crossing point are possible between curve 2 and 3. In this situation the theoretical given applied voltage cannot be applied. This corresponds to the experimental data showing a voltage limitation given by a strong back-corona.

3. BACK-CORONA EFFECT ON COLLECTION EFFICIENCY

3.1 Efficiency loss by positive particle charging

The back-corona current adds to the glow corona current, because the positive and negative ions move in opposite directions. On the contrary, the positive and negative charging effects on the particles subtract each other, leading to an average lower particle charge and lower particle collection efficiency.

The efficiency loss given by positive ions and by effects in particles need to be defined. Performance degradation due to back corona has the following characteristics [7]:

- (a) Zero degradation at currents below that required for back corona formation.
- (b) Increasing degradation with increasing current above that required for back corona formation.
- (c) The degradation is limited at currents above a saturation level.

The equation we use to link the efficiency without η and with the positive ions effects η' is:

$$\eta' = k_d + (1 - k_d) \left(\frac{J - J_b}{J + J_b} \right) \eta \quad (\text{Eq.5})$$

where J and J_b are the current density given by glow-corona and back-corona discharge and k_d is a coefficient optimized on experimental data[8][9].

The equation effects are twofold. It increases the efficiency degradation induced by the injected positive ions and defines an efficiency loss lower limit given by the constant k_d . The efficiency loss lower limit is typical of industrial electrostatic precipitator where the power supply control and the great numbers of collecting electrodes do not allow the back-corona discharge to attend the equilibrium conditions where the efficiency goes to zero. In this case we do use a k_d coefficient equals to 0.65.

In laboratory conditions and with a fixed applied voltage the saturation level goes near zero and k_d in stable conditions is null.

3.2 Efficiency computation

In order to compute the efficiency we used an iterative computation described and implemented in ORCHIDEE [12-14], comprehensive electrostatic precipitator modeling software. The iterations related to back-corona simulation are the following (see also Fig. 7):

1. Simulation of the electro-filter collection with a null particle layer thickness. The particle collection strongly depends on the effective collection voltage U_d that in this case is equal to the applied voltage U_a .
2. Computation of particle layer dynamics using the computed collection efficiency as well as the estimated influence of rapping and re-entrainment [15]. A useful result is the particle layer thickness.
3. Based on particle layer thickness estimation of the voltage drop U_l at the layer.
4. Computation of the glow-corona current and, if there are the inception conditions, back-corona current.
5. From this point a new computation cycle starts. Electrofilter collection is computed using the effective collection voltage ($U_d = U_a - U_l$). The collection efficiency includes the loss due to the back-corona if this discharge is active on the layer.
6. etc.

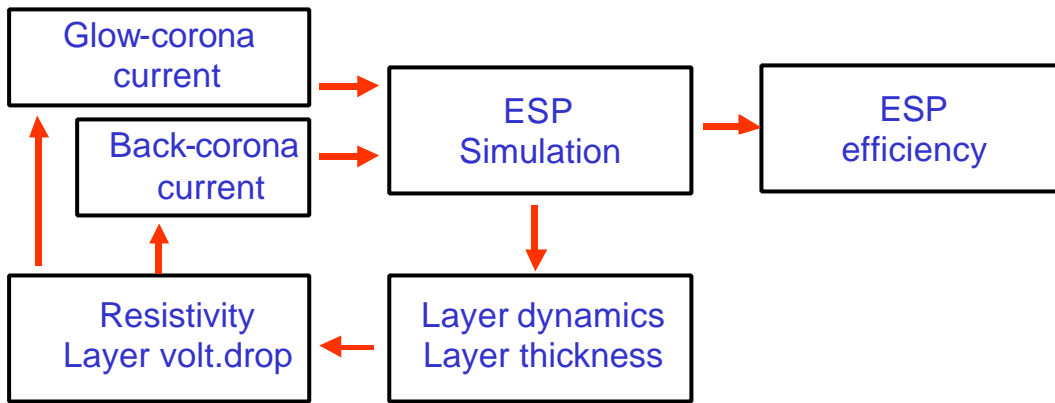


Fig. 7 Non-linear coupling between the different physical processes in ORCHIDEE 2

The needed iteration cycle depends on dust layer influence on efficiency. In most configurations little cycles allow a good estimation of collection efficiency.

We applied the efficiency computation to an industrial configuration (Le Havre) where the collecting distance between plates allow a comparison with migration velocity found in literature [8][9]. Fig. 8 shows a comparison of efficiency as function of particle layer resistivity. It is a qualitative comparison as the electrostatic precipitator details used in literature were not available. It can be seen that starting at a resistivity of about 10^{10} Ohm cm the efficiency start lowering and saturate at 10^{12} Ohm cm.

Even if further quantitative data are needed to fully validate the model, we have for the first time an electrostatic precipitator model that can estimate the efficiency of an industrial electrostatic precipitator as function of coal resistivity.

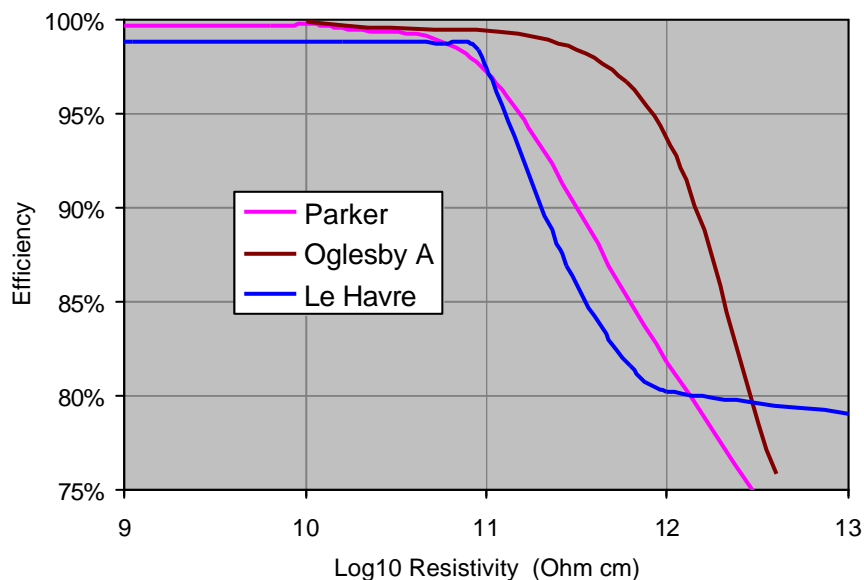


Fig. 8 Efficiency as function of particle layer resistivity

4. CONCLUSIONS

This paper presents for the first time a model reproducing the back-corona effects on voltage-current characteristics and on electrostatic precipitator efficiency.

The strict connection between the discharge at the emitter electrode and back-corona is quantitatively estimated. A simple electric scheme explains the positive feedback given by the particle layer resistivity on back-corona current. Efficiency loss estimation makes use of the back-corona electrical properties calculations and is coupled with the overall collection simulation.

The model simulation is implemented in a user-friendly electrostatic precipitator model (ORCHIDEE) already in use by coal power plant personnel [12]. Operating personnel can contribute to dust emission control on their unit

Practical application of this model including : estimating the impact of different type of coal on efficiency and making the right choice in coal blending, distinguishing voltage-current variation associated with faults or to particle resistivity variation, etc.

More studies can complete and refine this model as well as giving new uses. Future back-corona model applications include:

- Better power-supply controls making use of detailed modeling of glow and back corona discharge and allowing higher collection efficiency;
- Simulation in environment where back-corona is a known problem: cement plant electrostatic precipitators and Surface coating equipment
- Model extension to describe the more general back-discharge [10] of which back-corona is the low current part

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