Mutual exchange of charged particles in high voltage dc devices insulated by high vacuum*

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HVPTF description

Stainless Steel vacuum chamber volume 2.4 m³

Double polarity configuration
2 Cockcroft-Walton power supplies
400kV\(_{\text{DC}}\) -1mA (positive and negative unit put in series),
Maximum voltage: 800kV\(_{\text{DC}}\)

Vacuum & gas injection system
1 turbomolecular pump 1m³/s baked by a dry scroll pump 0.04 m³/s,
pressure from 3e-7 to 1e-02 mbar

Measured quantities
✓ pressure : 1 capacitive, 1 hot cathode and 1 penning pressure gauge [mbar]
✓ Equivalent Dose Rate (EDR) [\(\mu\text{Sv}/\text{h}\)]
✓ Voltages (U+, U-) [kV], Currents (I+, I-) [mA]
✓ Residual Gas Analyser (RGA) , 1-100 [amu]
✓ X-ray spectra two type of scintillators [keV]
✓ Ifra-Red Camera [°C]

Ref. [1]
Breakdowns usually occur between electrodes under test but ...
Interaction with the vacuum chamber wall

“Spurious“ micro discharge activities occur between single power supply and the grounded vacuum vessel

- $I^+ > I^-$, sometimes occurs also the opposite ($I^- > I^+$)
- Temperature rise only on the metallic cantilever structure connected to the positive power supply has been observed
- No visible glow discharges
- No hot spots on the support of the negative electrode
- No hot spots on the vacuum chamber inner wall
Visual inspection of the surfaces exposed to vacuum

- Brown stains have been observed on:
  - On the inner wall of the vacuum chamber
  - On ceramic insulator (positive feed through) in a region with no electric field
- Annular regions without stains are in front of each support
- Traces of metallic fusions can be observed by naked eye on the cylindrical support sustaining each electrode
The brown layer composition is compatible with Iron and Chromium, the layer appears very thin ($t_k < 1\text{mm}$). Fe and Cr are consistent with the composition of the stainless steel which is the sole metal adopted for the vacuum chamber and for the electrode under test. The expansion of metal vapors is indicated.
“After X-ray irradiation (curve c) the glass shows strong solarization effects with broad bands in the UV near 200 nm and in the visible range near 450 nm which cause a yellow to brown color. The color centers produced had a great stability at room temperature.” D. Ehrt and W. Vogel “Radiation effect in glasses” Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms Volume 65, Issues 1–4, 1 March 1992, Pages 1-8
Test sequence:
1) system conditioned by automatic conditioning procedure
2) Voltages kept constant at 320 kV (-160kV, +160kV)
3) wait sufficient time in order to quench any microdischarge activity
4) at t > 3270 s, only the voltage of the negative power supply was manually decreased step by step
5) at -150kV ; 160kV the microdiscarges restarted at the positive side (I+ > 0.1 mA) although |V-| was decreasing
The microdischarge activity has involved mainly the vacuum vessel and the positive power supply rather than the two electrodes. The peculiar spatial distribution of the emission sites on the electrode surfaces, has been analyzed thanks to the idea proposed in [*] where a mutual exchange of charged particles, with opposite sign, is simulated between electrodes having a generic shape.

\[
A \cdot B + C \cdot D \geq 1
\]

\[
B := \frac{\Gamma_{\text{electrons}}}{\Gamma_{+ \text{ions}}} \quad D := \frac{\Gamma_{\text{electrons}}}{\Gamma_{\text{photons}}} \quad A := \frac{\Gamma_{+ \text{ions}}}{\Gamma_{\text{photons}}} \quad C := \frac{\Gamma_{\text{photons}}}{\Gamma_{\text{electrons}}}
\]

A steady interchange of charged particles and photons between cathode and anode is one of the hypothesis proposed in the past literature [**] to explain breakdown events over long vacuum gaps. Direct measurements of coefficients A and B carried out by the same authors, and others [***] would not immediately support the validity of such equation.

- Trump J G and Van De Graaff R J 1946 J. Appl. Phys 18 327
- Filosofo I and Rostagni A 1949 Phys. Rev. 75, 1269
Mutual exchange of charged particles: the Discharge attractors

Red trajectories ➔ positive charge particles
Black trajectories ➔ negative charge particles

The trajectories have been grouped and exchanged only between two points A and C, respectively on the anode support and the cathodic surface of the vacuum vessel. Such points are called discharge attractors as referred in [*]

It is possible to demonstrate that the trajectory path of a charged particle in an electrostatic (irrotational) field, assuming classic motion and zero initial velocity, depends only on the shape of the domain and the ratio of the applied voltages (in case of multi-electrode system).

Under such conditions the attractor locations depend only on the shape of the electrodes and on the ratio between the applied voltages.

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Conclusions

- Experimental evidences concerning the existence of accumulation points during occurrence of micro-discharges have been observed during the high voltage conditioning of an electrostatic device insulated by large vacuum gaps.
- A mutual exchange of positive-negative charged particle is the mechanism which presumably causes this phenomenon and defines the position of the micro-discharge attractors.
- The attractors regions due to the regenerative processes of charged particles between cathode and anode have been identified thanks to numerical ray-tracing simulations.
- The position of the attractors depends only on electrode shape and the ratios of applied voltages.
- A perturbation of the trajectories position by altering the voltage distribution has been sufficient to initiate the micro discharge occurrence.
- The existence of phenomena able to concentrate the dissipation of power in specific location on the electrode surfaces during the high voltage conditioning in vacuum could be exploited in the development of neutrons sources applications.
References

1) N. Pilan et Al. “Evidences of accumulation points in cascade regenerative phenomena observed in high voltage dc devices insulated by vacuum” published in Journal of Physic Communications (IOP) https://doi.org/10.1088/2399-6528/aaea95
3) N. Pilan et Al. “Study of High Voltage Direct Current breakdown between stainless steel electrodes separated by long vacuum gaps”, to be published in Nuclear Fusion
7) K. Watanabe, M. Mizuno and Y. Ohara, “DC voltage holding of vacuum gap for high-energy ion sources” J. Appl. Phys. 72 (9) , 1 November 1992
12) N. Pilan, A. De Lorenzi, P. Veltri: “Voltage Holding Prediction in Multi Electrode–multi Voltage Systems Insulated in Vacuum” IEEE Transactions on Dielectrics and Electrical Insulation Vol. 18, No. 2; April 2011