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PlasMa: teoria e simulação avançada de plasmas relevantes para aplicações energéticas

Código do projeto | M1420-01-0145-FEDER-000016

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Analyzing experimental data on ignition of corona discharges and breakdown on positive electrodes in high-pressure air for diagnostics of surface microprotrusions

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9th International Workshop on Mechanisms of Vacuum Arcs

March 11, 2021

Outline

- The work concerns modeling of experiments on high-pressure gas discharges - why presenting it at MeVArc?

- Modeling experiments on corona ignition and breakdown on positive electrodes in high-pressure air

- Conclusions

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Why presenting this work at MeVArc?

- Understanding the **mechanism of enhancement of field electron emission** from cold cathodes **is a key to understanding vacuum breakdown**.
- Quite a few cutting-edge experimental investigations of vacuum breakdown have been reported, however there is still no universal understanding of the emission enhancement mechanism. **The hypotheses include**:
  - ➢ Amplification of the applied electric field by microprotrusions present on the electrode surface;
  - ➢ Local reduction of the work function of the cathode material (e.g., lattice defects or adsorbed atoms);
  - ➢ `Nonmetallic' electron emission mechanism;
  - ➢ Enhancement of field emission by waves confined to the metal surface (plasmons);
  - ➢ Mobile dislocation dynamics near the cathode surface; …
- Is it possible to consider a **targeted experiment which**, while not giving information of the breakdown phenomenon on the whole, **would allow checking one of these hypotheses?**

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Why presenting this work at MeVArc?

Do microprotrusions exist on electrode surfaces?

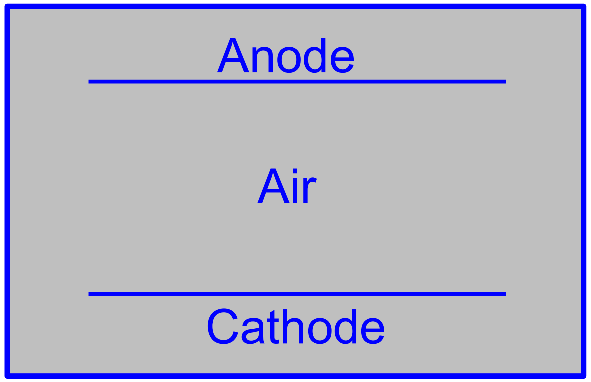
- **Not seen in SEM images** taken in this community (CERN, Jerusalem).
- **Gas-Insulated Switchgear (GIS) industry** (Siemens, ABB, Hitachi) has no doubts that the protrusions do exist:

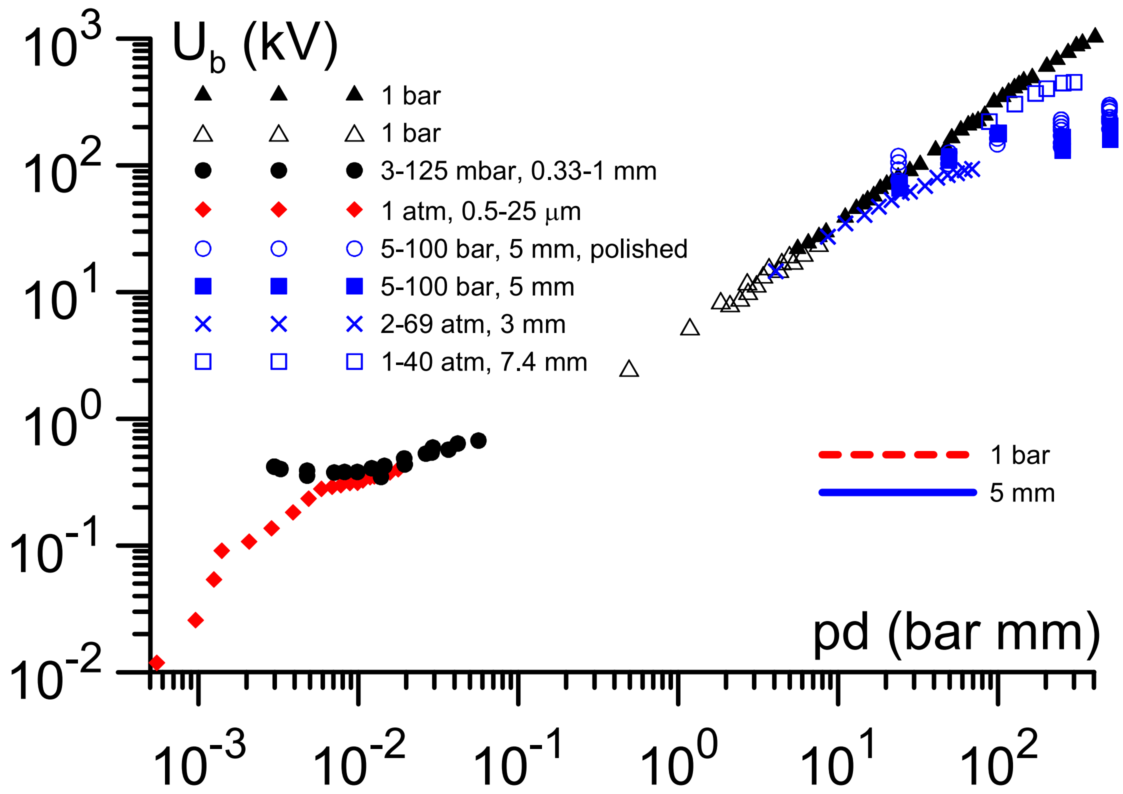
  Protrusions of small lengths of a few 10 to few 100 μm correspond to the surface roughness, whereas long protrusions of more than 500 μm correspond to particulate contamination or severe surface damages.

  A 2020 paper from ABB Motion and Hitachi ABB Power Grids Research

- Maybe, the materials are different?
- A **targeted experiment which would allow to independently and unambiguously check the existence of protrusions** is needed.
- Two **possible candidates:**
  - Deviations from Paschen's law in experiments on **breakdown of parallel-plate** gaps in the case of microgaps and at very high pressures;
  - Deviations from the similarity law in experiments **on corona ignition and breakdown on positive electrodes** at very high-pressure gas.

Deviations of breakdown voltage from Paschen's law





Air breakdown in uniform field. Black: data from E. Kuffel, W. S. Zaengl, and J. Kuffel, *High Voltage Engineering*, 2nd ed. (Newnes, Oxford, 2000). Blue: data for very high pressures (up to 40-100 bars). Red: microgaps (0.5-25 μm).

- **Paschen's law** (black points) describes the **breakdown voltage in plane-parallel gaps**.
- There are **deviations of the measured breakdown voltage** from Paschen's law in **microgaps** (red points) and at **very high pressures** (blue points).

Model of low-current discharges in air

- A **'minimal' model and kinetic scheme of low-current discharges in air** at pressures of the order of atmospheric and higher.
- **Equations**:
  - Conservation and transport of charged species (drift-diffusion approximation);
  - Poisson;
  - Three-exponential Helmholtz (photoionization).
- **Charged species**: electrons, one effective species of positive ions, O_2^-, O^-, O_3^-.
- **Plasmachemical processes**:
  - Electron impact ionization;
  - Photoionization;
  - Two-body (dissociative) and three-body attachment;
  - Collisional detachment from O_2^- and associative detachment from O^-;
  - Charge transfer from O^- to O_2^- and conversion of O^- to O_3^-;
  - Ion-ion and electron-ion recombination.

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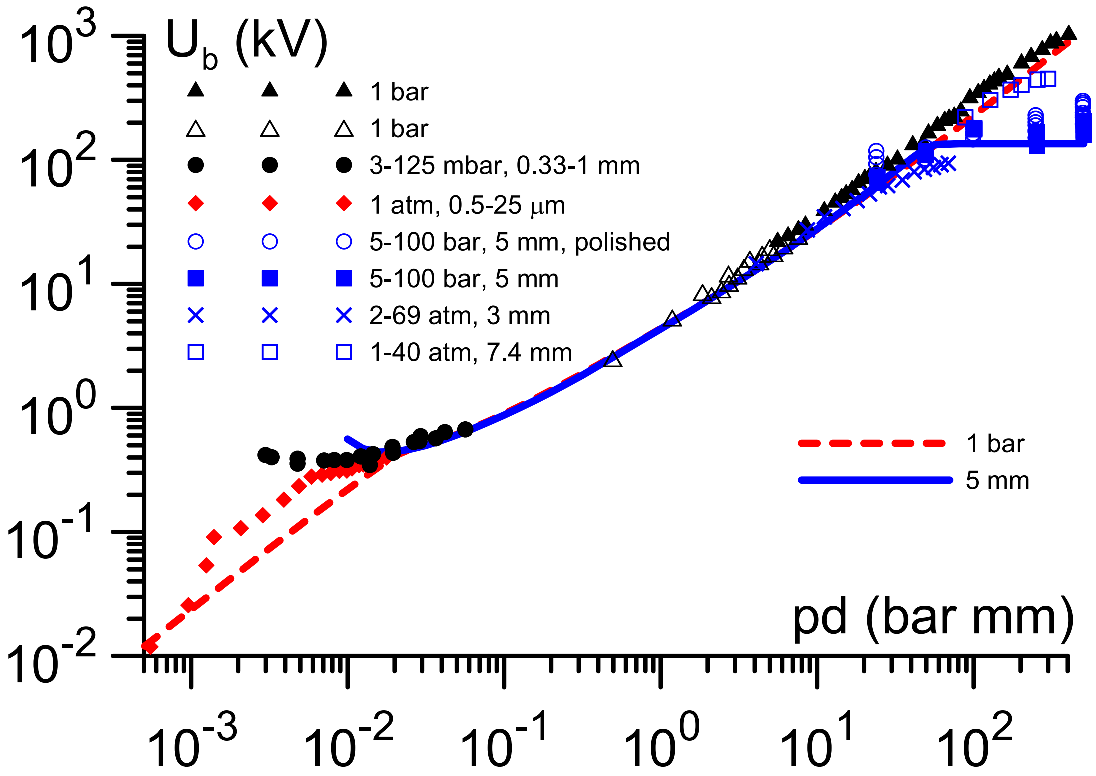
Deviations of breakdown voltage from Paschen's law

- **Computations with the field emission** with the **enhancement factor β = 50** are in qualitative agreement with the deviations observed in experiments for both **microgaps** and **high pressures**. (Our point of view at MeVArc 2019.)
- The GIS industry (Siemens, ABB, Hitachi) has **another explanation**: **enhanced ionization of neutral gas molecules** in regions of increased electric field near the protrusions on the surface of the electrode, which is **also in agreement with experiments**.



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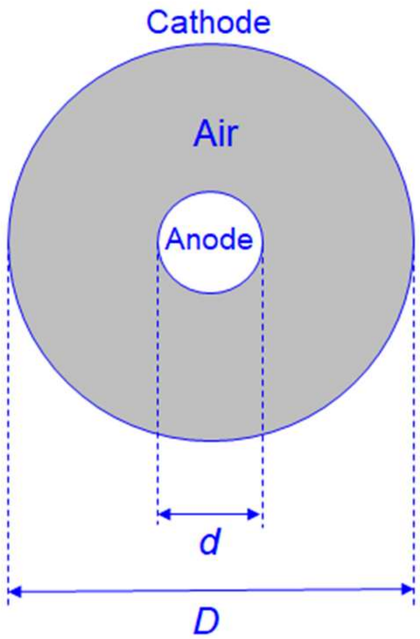
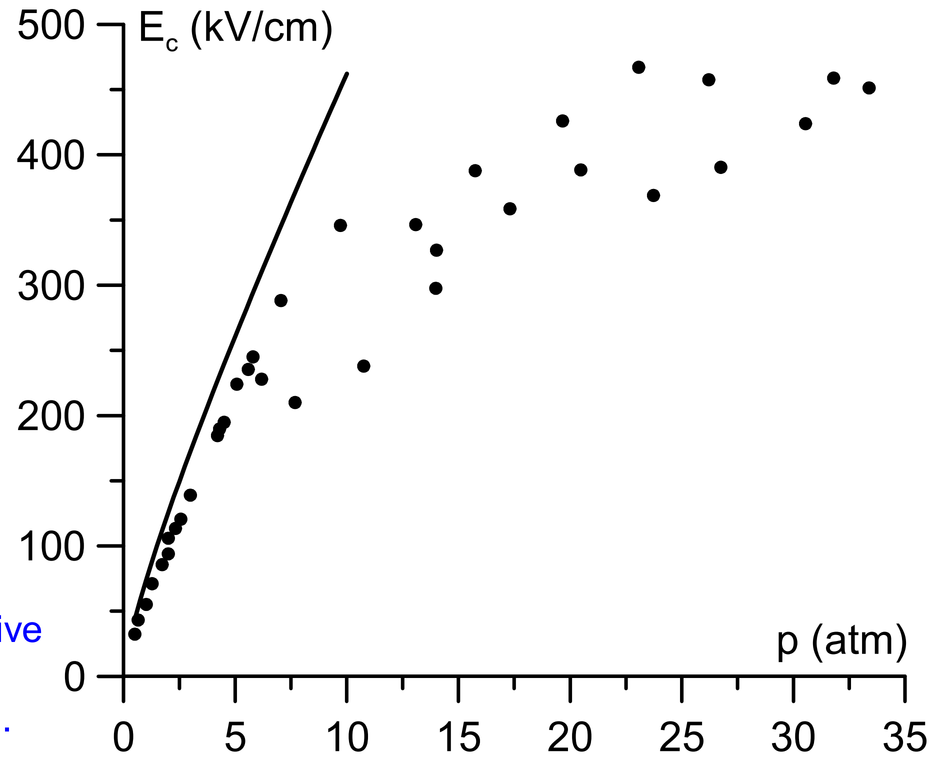
=> This does not allow a unique interpretation! (Not a viable candidate.)

Deviations from similarity law at small electrodes (high *p*)





Ignition field of positive corona. Points: data from Robinson 1969.

- The Peek's formula for concentric cylinder electrodes of **small radii** (one of forms of the **similarity law)** is an equivalent to Paschen's law for plane-parallel gaps.
- The Peek's formula is valid for *p* <~ 5 atm.
- At *p* >~ 5 atm, **deviations from the similarity law** occur.
- Cathodic phenomena are irrelevant and **enhanced ionization of neutral gas** in **regions near protrusions on the anode surface** is the only possible explanation.

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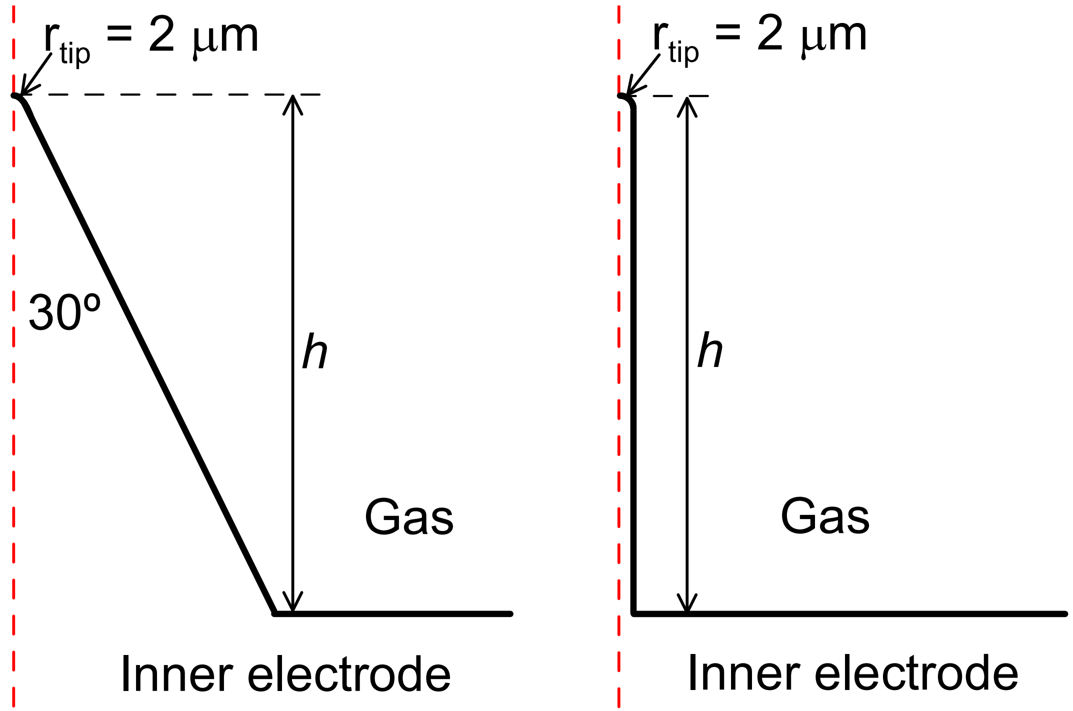
Deviations from similarity law at small electrodes (high *p*)

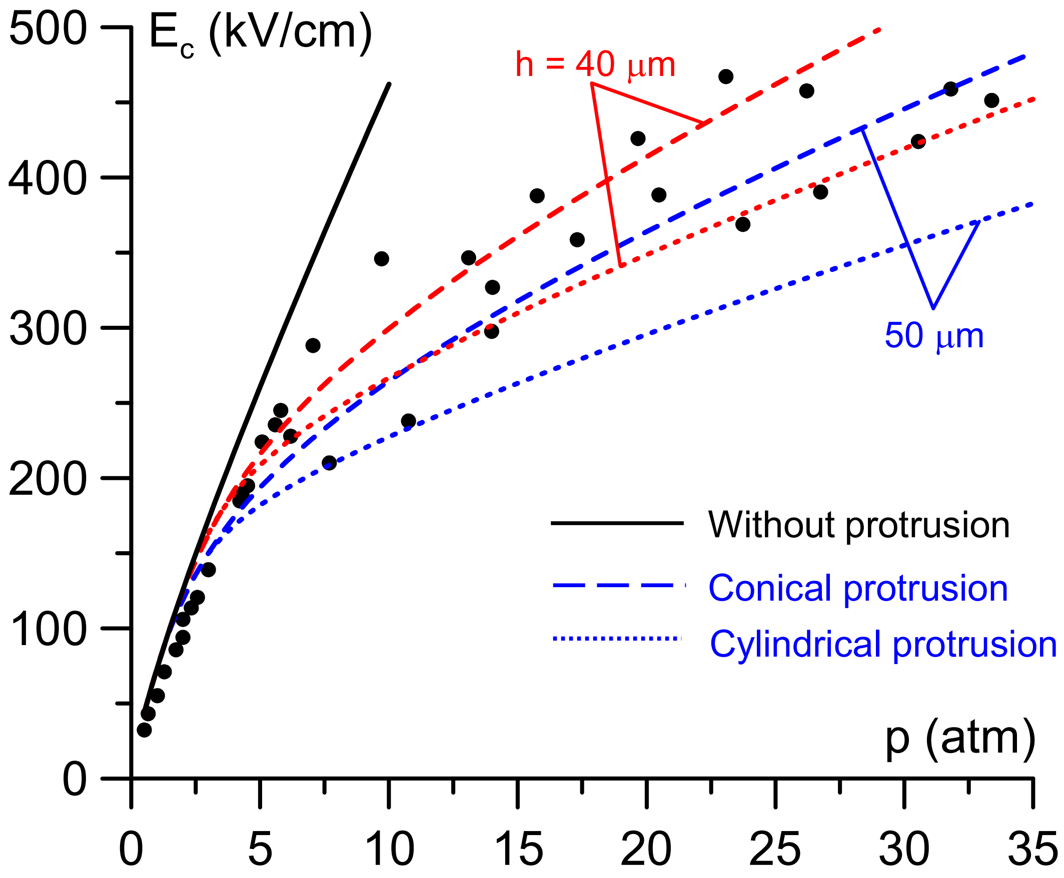
- The goal is to **study qualitatively** the **effect of microprotrusions**, present on the surface of the inner electrode, **over the discharge ignition voltage** under conditions of experiments with **concentric cylinder electrodes**.
- In this work, a **single cylindrical or conical protrusion** on the surface of the inner electrode is considered.



Schematic representation of the conical protrusion with a 60º full aperture angle and a spherical tip with a radius of 2 μm (a), and the cylindrical protrusion of a radius of 2 μm and a (half-)spherical tip of the same radius (b).

Deviations from similarity law at small electrodes (high *p*)

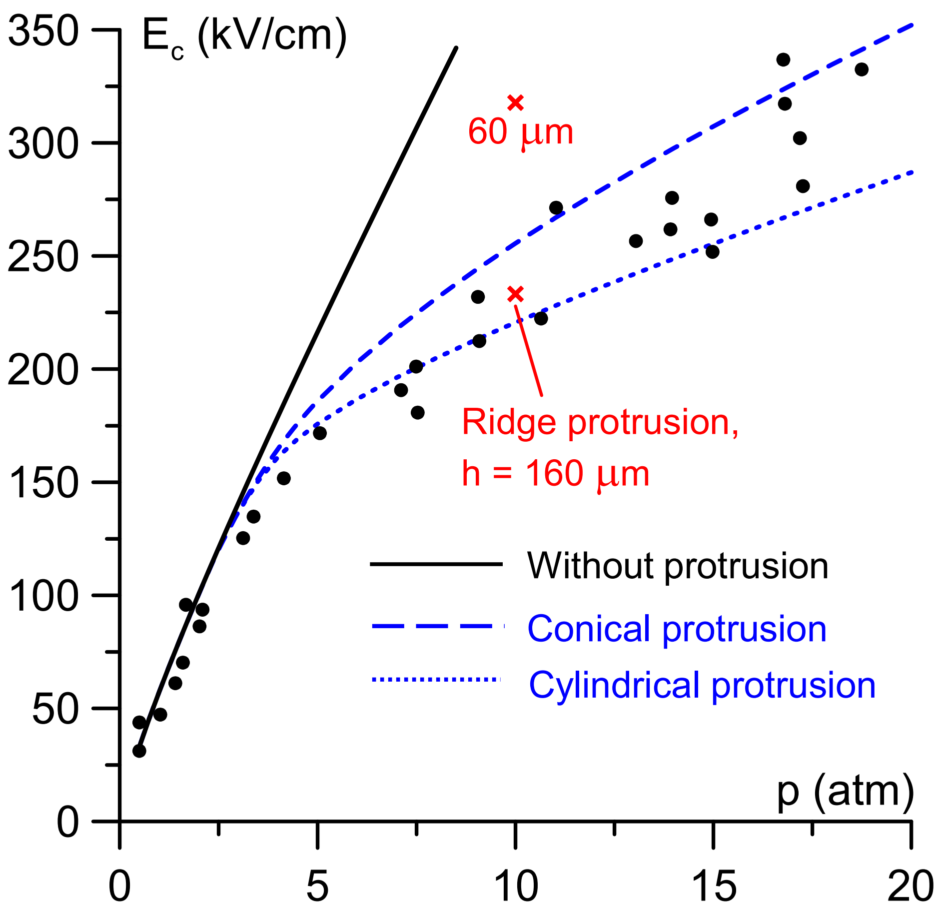
- The **computed ignition field** is close to the experimental values in the **pressure range of 0.5 - 3 atm**: the **effect of protrusions is negligible** and the similarity law and Peek's formula hold.
- The **presence of a protrusion** results in a **reduction of the macroscopic ignition field** due a higher local electric field and, consequently, substantially increased ionization in the vicinity of the protrusion. The **effect comes into play** at pressures of the order of **5 atm**.



Ignition field on a positive electrode, *r* = 1.2 mm. Lines: modeling without account of protrusions (solid) and with account of a conical (dashed) or cylindrical (dotted) protrusion of height *h*. Points: experiment Robinson 1969.

Deviations from similarity law at small electrodes (high *p*)

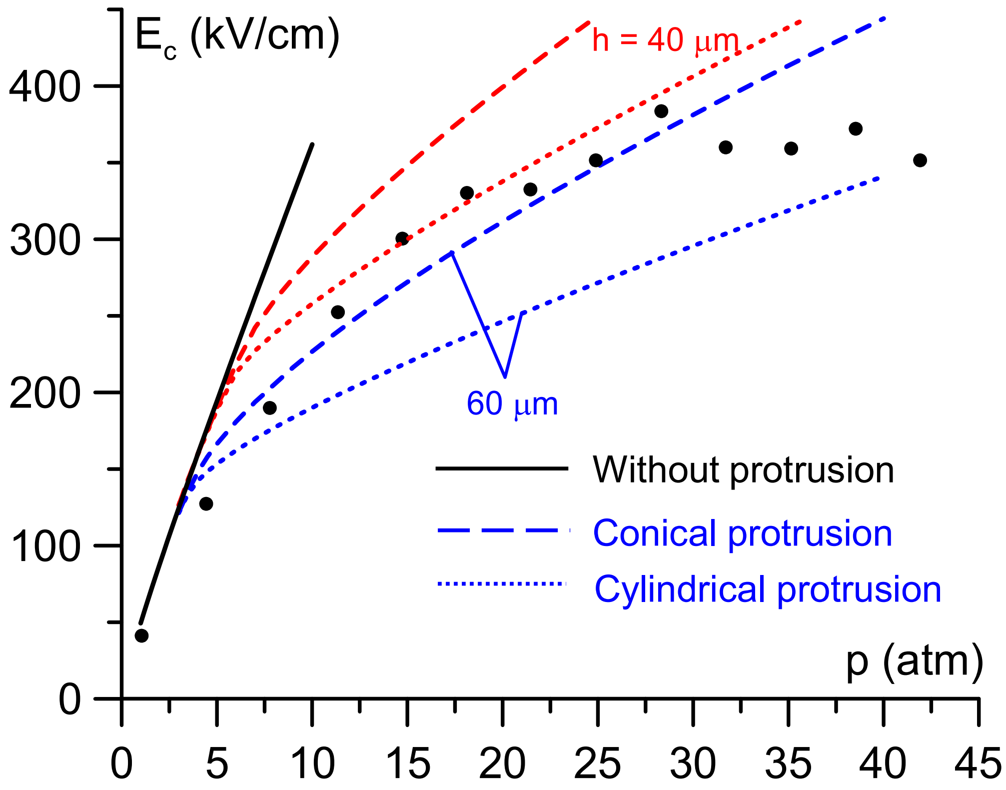
- Again, the **computed ignition field** is close to the experimental values. The **effect comes into play** at pressures of the order of **5 atm**.
- For comparison purposes, also shown are simulations for **concentric cylinder electrodes with a long ridge at the surface of the inner cylinder**, parallel to the cylinder axis (60º full aperture angle; cylindrical rounding of 2 μm radius at the tip).
- One can see that **ridge protrusions must have a bigger height than conical ones** for a comparable effect.



Ignition field on a positive electrode, *r* = 3.18 mm. Lines: modeling without account of protrusions (solid) and with account of a conical (dashed) or cylindrical (dotted) protrusion of height of 50 μm. Crosses: modelling, concentric cylinder electrodes with a ridge protrusion of height *h*. Points: experiment Robinson 1969.

Deviations from similarity law at small electrodes (high *p*)

- Again, the **computed ignition field** is close to the experimental values. The **effect comes into play** at pressures of the order of **5 atm**.
- The experimental data manifest saturation of the breakdown field in the range *p* ~> 30 atm, whereas the modeling does not. However, the author mentioned that the measurements were uncertain at higher pressures and a reproducible breakdown voltage measurement was hard to perform.
- The **protrusion heights necessary to achieve a qualitative agreement with the experiment** are of the **order of 50 μm** in all the cases.



Ignition field on a positive electrode, *r* = 6.35 mm. Lines: modeling without account of protrusions (solid) and with account of a conical (dashed) or cylindrical (dotted) protrusion of height *h*. Points: experiment Howell 1939.

Conclusions

- **We do not say that such protrusions do exist on technical materials** (although colleagues from Siemens, ABB, and Hitachi do think so); and in any case it's not up to us theorists to say so.
- We **only say that there are experiments that can be explained only in this way**.
- A **methodologically correct approach** would be to perform similar experiments with **the materials of relevance to this community**.
- **If no deviations from the similarity law have been found**, then the GIS and accelerator materials are different and the latter have no protrusions (at least not of a comparable size).
- And if the deviations are found, then we will need to reconcile these results with the existing measurements.
- The experiments by themselves are simple; needless to say that there are always problems of man-months, time slots, funding etc, but a **methodologically correct approach usually pays out**: a targeted experiment can be a useful supplement to experiments on such a complex phenomenon as vacuum breakdown.