Technological Aspects: High Voltage

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Uses of High Voltage in Particle Accelerators

- Extracting beams (up to 50 kV)
- Accelerating beams (up to 28000 kV)
- Initiating discharges / pre-ionising gases (up to 20 kV)
- Focusing and deflecting beams (up to 50 kV)
- Suppressing unwanted particles (up to 5 kV)

Ion sources are particularly challenging for HV design

Explosive gasses (hydrogen)

High temperatures

Other contaminants (e.g. Cs)

Magnetic fields

Large amounts of charge carriers

Stray beams: electrons and ions

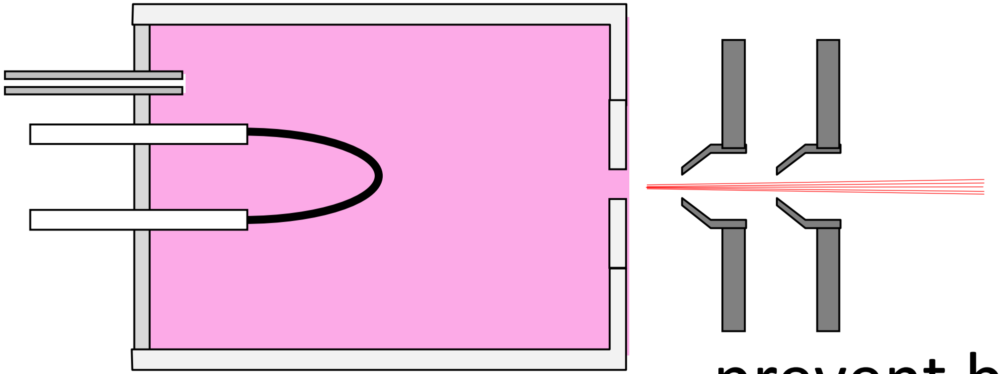
X-rays

Compact design

Main aim of high voltage design:

Produce reliable breakdown

... where we want it



prevent breakdown

...where we don't want it

Electrical Breakdown

- Global Breakdown
  - Complete rupture or failure of the insulation between two electrodes
- Local Breakdown
  - Partial breakdown of part of the insulation between two electrodes

Electrical Breakdown

- Electric field strength is the primary factor
- In general electrical breakdown is most likely to occur where the electric field is highest, but this depends on:
  - Materials and gasses
  - Pressures
  - Temperatures
  - Surfaces
  - Magnetic fields
  - Stray beams
  - Charges
  - Photons

Electric Field

- Potential gradient, electric field strength, electric field intensity, stress, E
- Units of Vm^{-1}, kVm^{-1}, $kVmm^{-1}$, $kVcm^{-1}$
- Equations, Analytical , Empirical, Numerical

$$E = \frac{V}{d}$$

Maxwell's Equations

$$\nabla \times \mathbf{H} = \mathbf{J} + \frac{\partial \mathbf{D}}{\partial t}$$

For electrostatic fields:

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t} \quad \Rightarrow \quad \nabla \times \mathbf{E} = 0 \quad \Rightarrow \quad \mathbf{E} = -grad\phi$$

$$\mathbf{D} = \varepsilon \mathbf{E}$$

$$\nabla \cdot \mathbf{B} = 0$$

$$\nabla \cdot \mathbf{D} = \rho \quad \Rightarrow \quad \nabla \cdot \mathbf{D} = \rho \quad \Rightarrow \quad \nabla^2 \phi = \frac{\rho}{\varepsilon}$$

or

Poisson's Equation
$$\frac{\partial^2 \phi}{\partial x^2} + \frac{\partial^2 \phi}{\partial y^2} + \frac{\partial^2 \phi}{\partial z^2} = \frac{\rho}{\varepsilon}$$

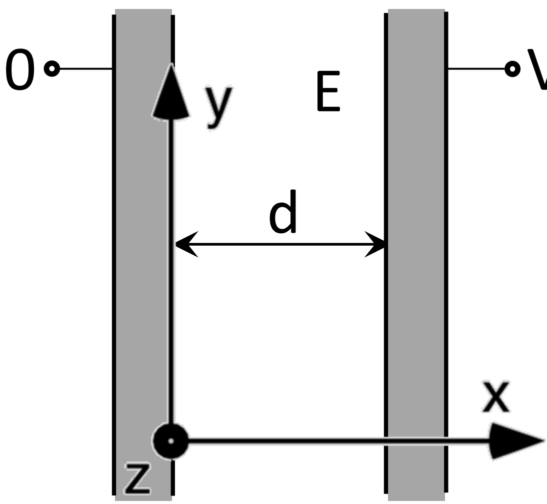
if $\rho = 0$:

Laplace's Equation
$$\frac{\partial^2 \phi}{\partial x^2} + \frac{\partial^2 \phi}{\partial y^2} + \frac{\partial^2 \phi}{\partial z^2} = 0$$

Using Laplace's Equation

$$\frac{\partial^2\phi}{\partial x^2}+\frac{\partial^2\phi}{\partial y^2}+\frac{\partial^2\phi}{\partial z^2}=0$$

Infinite parallel plates:



φ does not vary with *y* or *z*: $\frac{\partial\phi}{\partial y}+\frac{\partial\phi}{\partial z}=0$

$$\therefore \frac{\partial^2\phi}{\partial x^2}=0$$

$$\Rightarrow \frac{\partial\phi}{\partial x}=c_1$$

$$\Rightarrow \phi(x)=c_1x+c_2$$

At x = 0, $\phi=0$ and at x = d, $\phi=V$

$$\therefore c_1=\frac{V}{d} \quad \text{and} \quad c_2=0$$

$$\therefore \phi(x)=\frac{V}{d}x$$

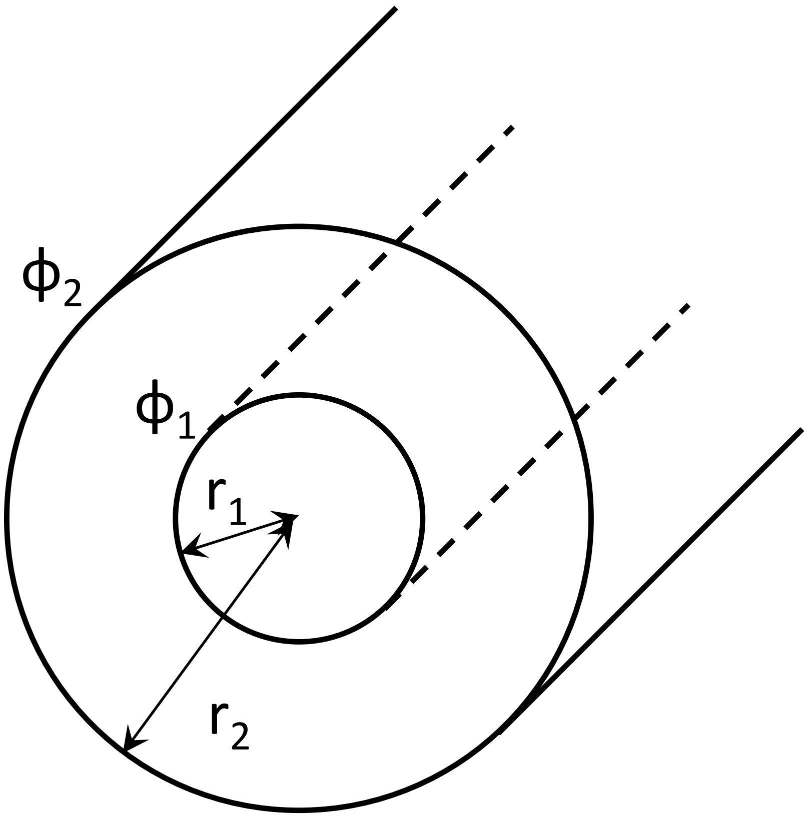
$$\mathbf{E}=-grad\phi$$

$$\therefore \mathbf{E}=-\frac{V}{d}$$

$$\Rightarrow \boxed{|\mathbf{E}|=\frac{V}{d}}$$

Similarly....

$$\frac{1}{r}\cdot\frac{\partial}{\partial r}\left(r\frac{\partial\phi}{\partial r}\right)+\frac{1}{r^2}\frac{\partial^2\phi}{\partial\varphi^2}+\frac{\partial^2\phi}{\partial z^2}=0$$



$$\phi(r)=\phi_1+\frac{\phi_1-\phi_2}{\ln\left(\frac{r_1}{r_2}\right)}\left(\ln r-\ln r_1\right)$$

$$E(r)=\frac{\phi_1-\phi_2}{r\ln\left(\frac{r_2}{r_1}\right)}$$

$$E_{\max}=\frac{\phi_1-\phi_2}{r_1\ln\left(\frac{r_2}{r_1}\right)}$$

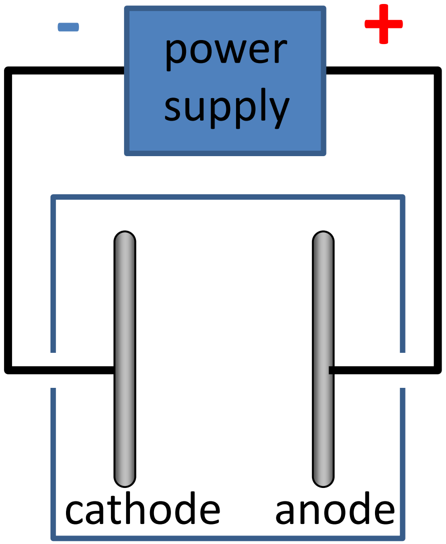
Fine for simple geometries...

thankfully we have computers

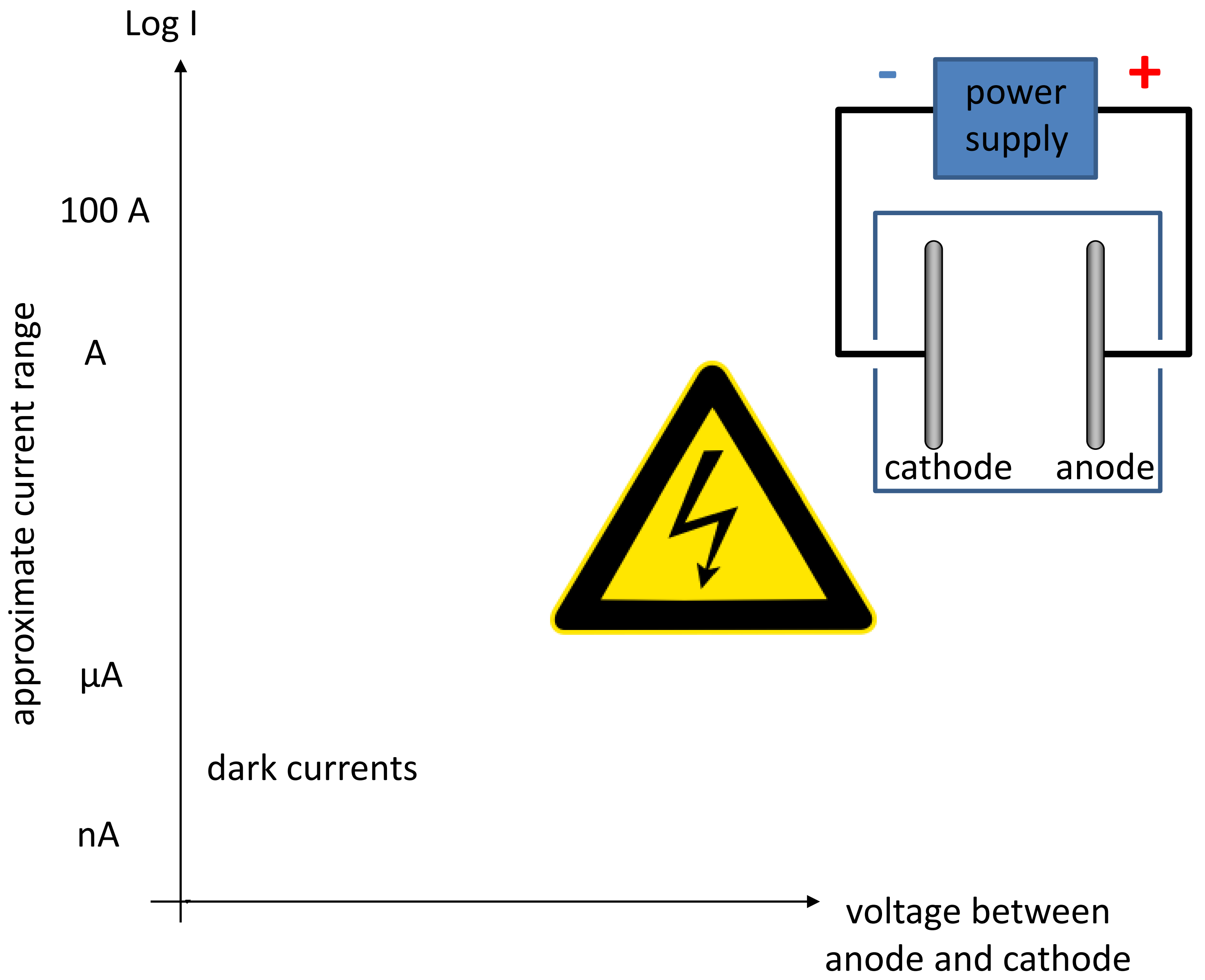
3D Modelling Software- Commercial and Open Source

Plus many others...

Electrical Discharges



Electrical Discharges



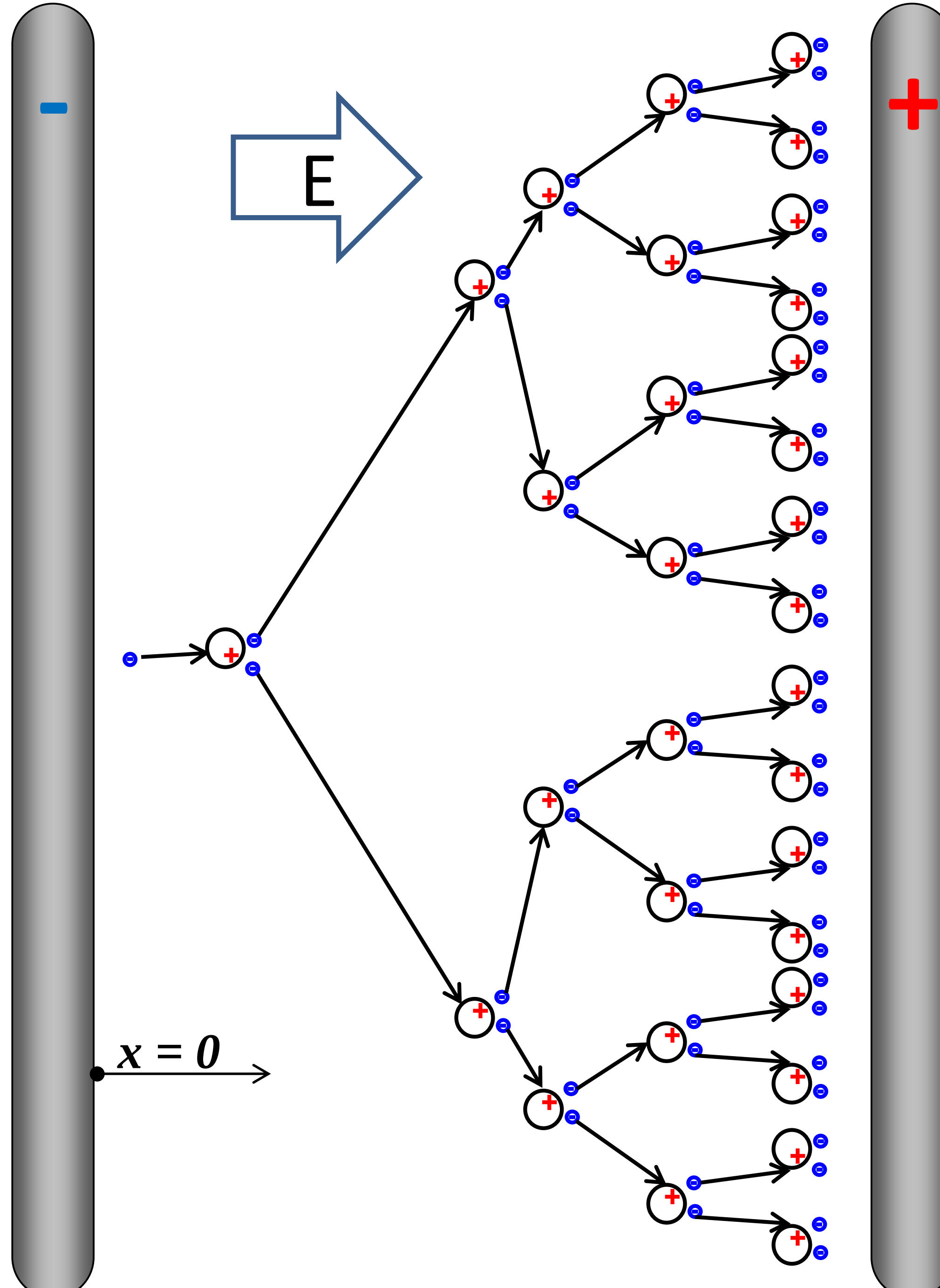
Avalanche

John Townsend
"Townsend discharge"
1897

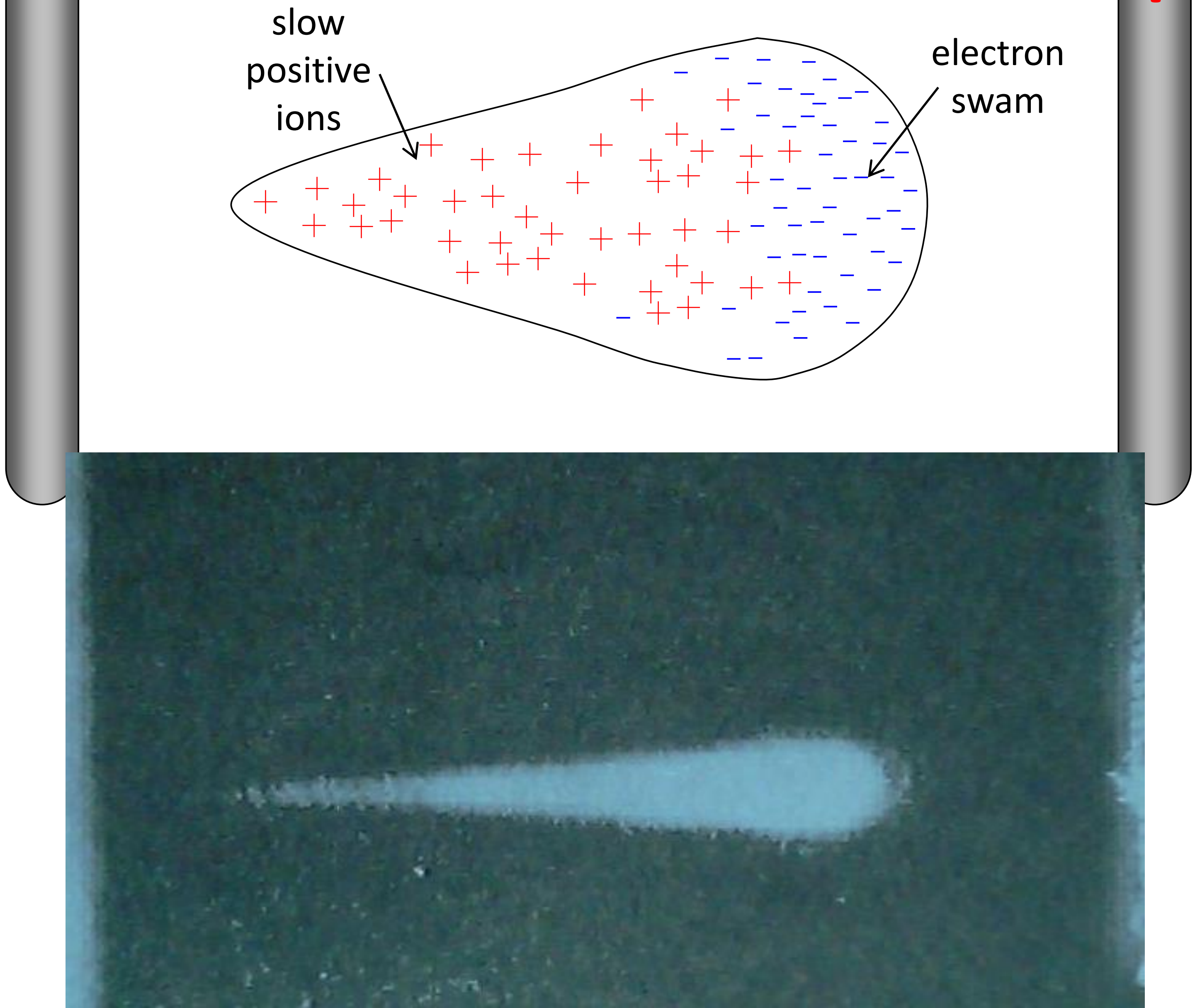
$$dn_x = n_x \alpha dx$$

By integration and $n_x = n_0$ at $x = 0$

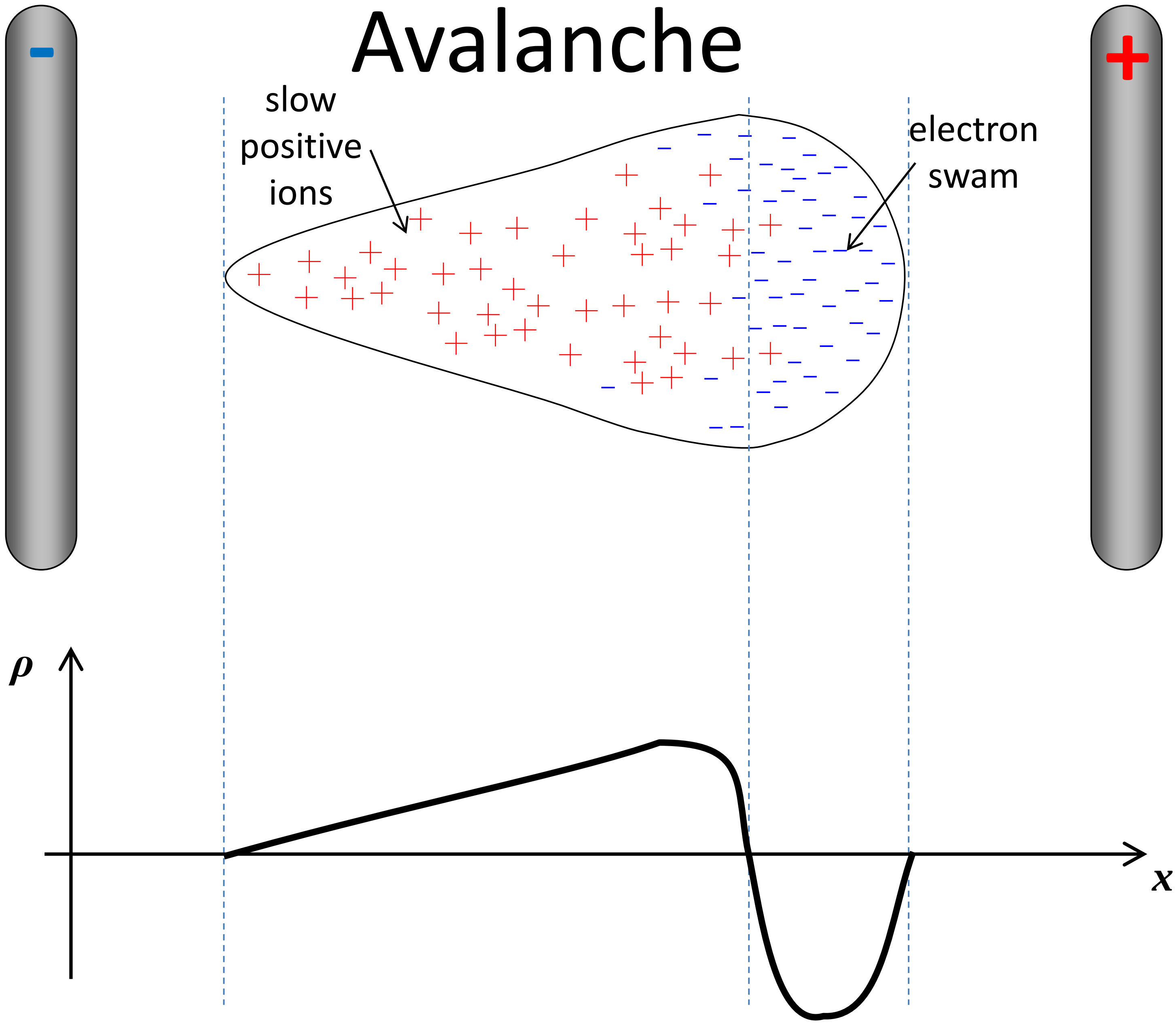
$$n_x = n_0 e^{\alpha x}$$



Avalanche



Avalanche



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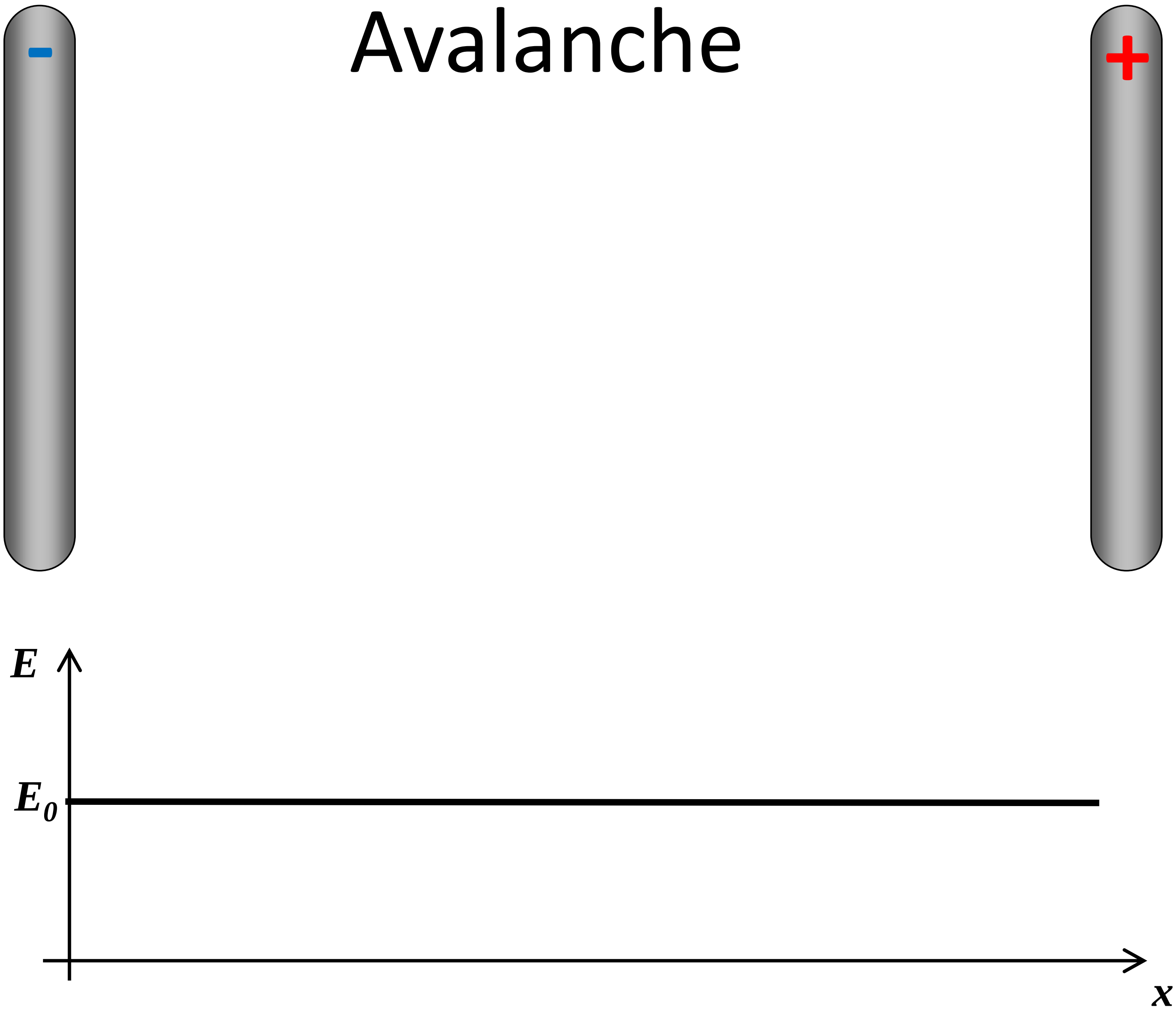
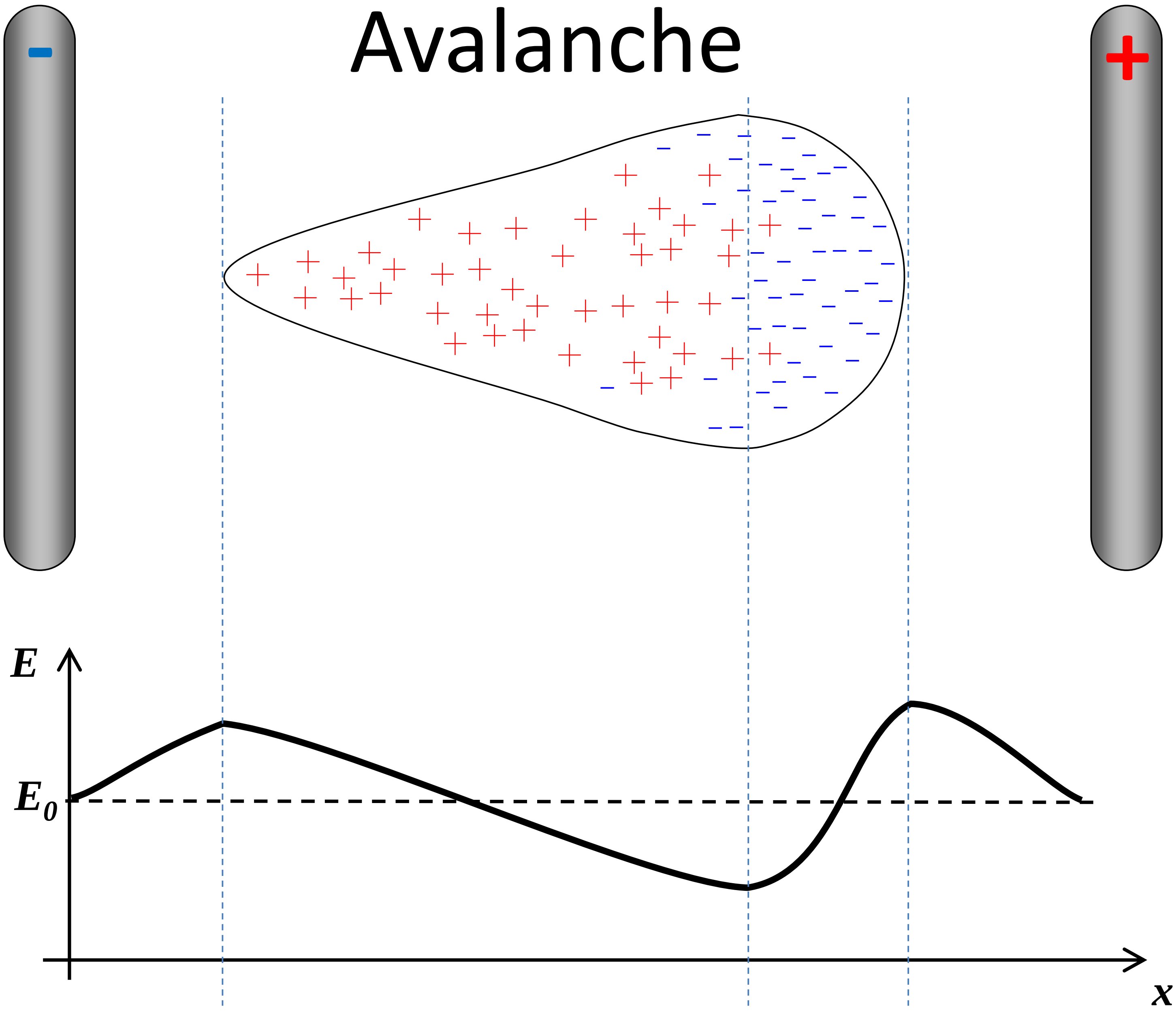
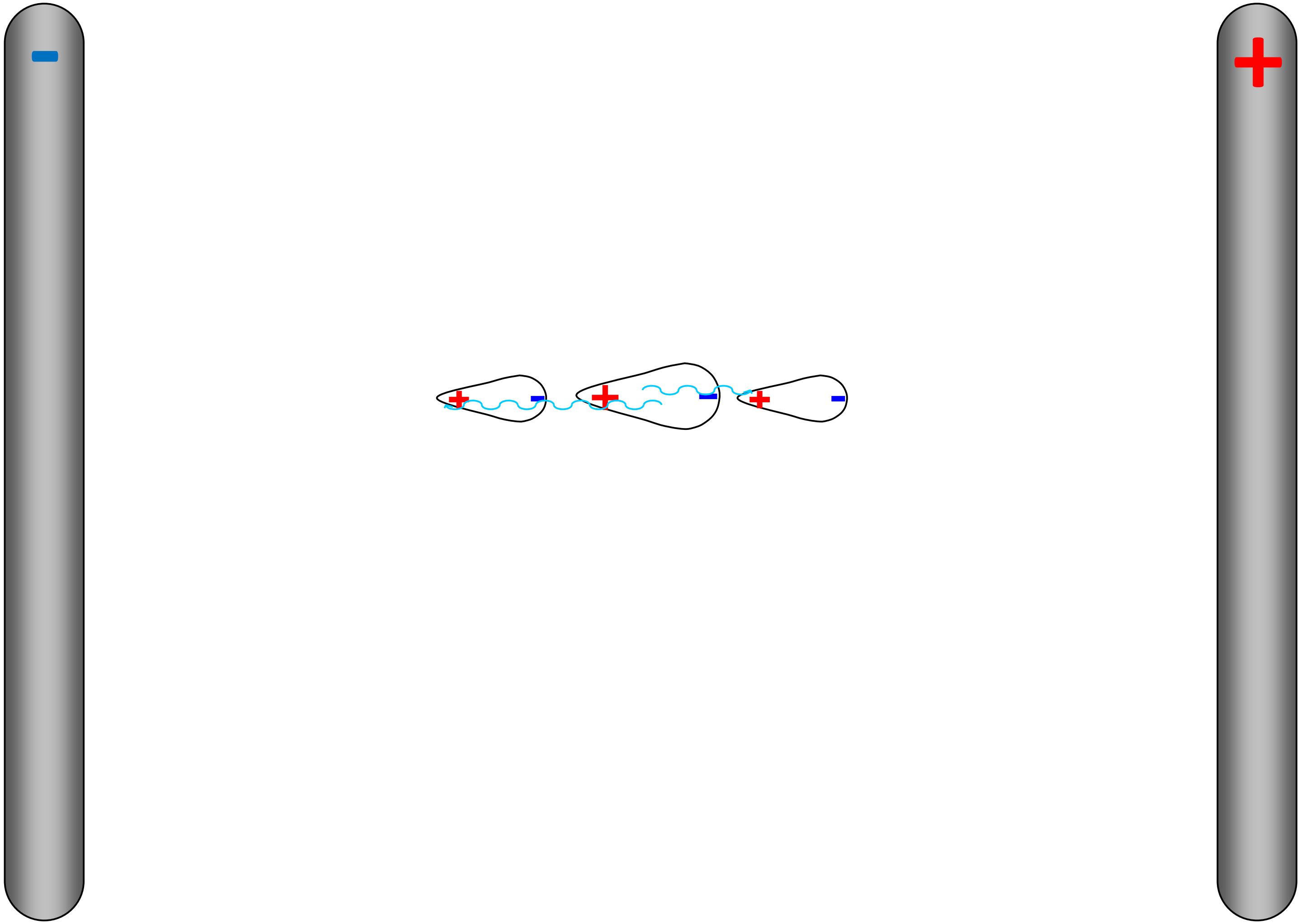


Avalanche



Streamer



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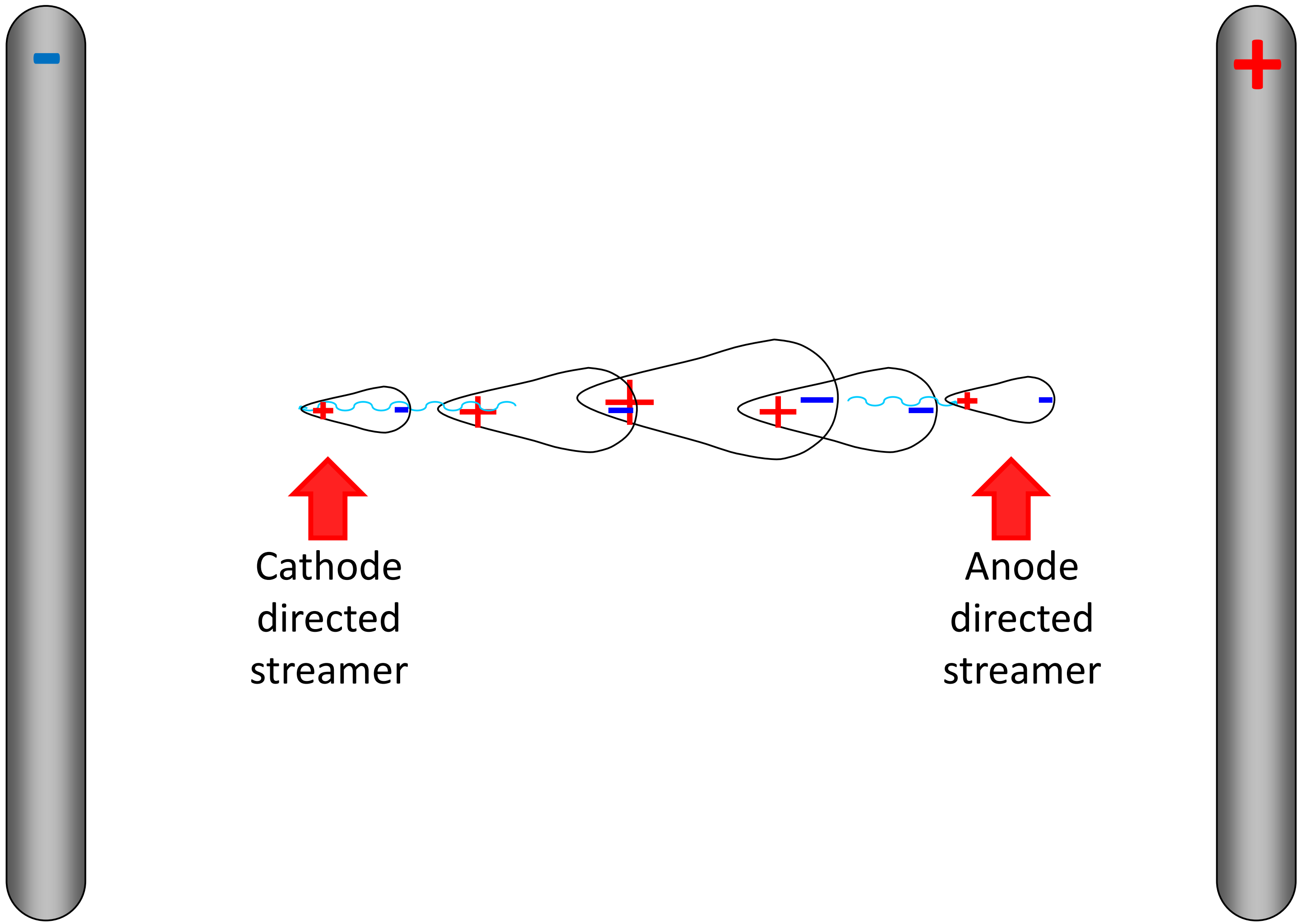

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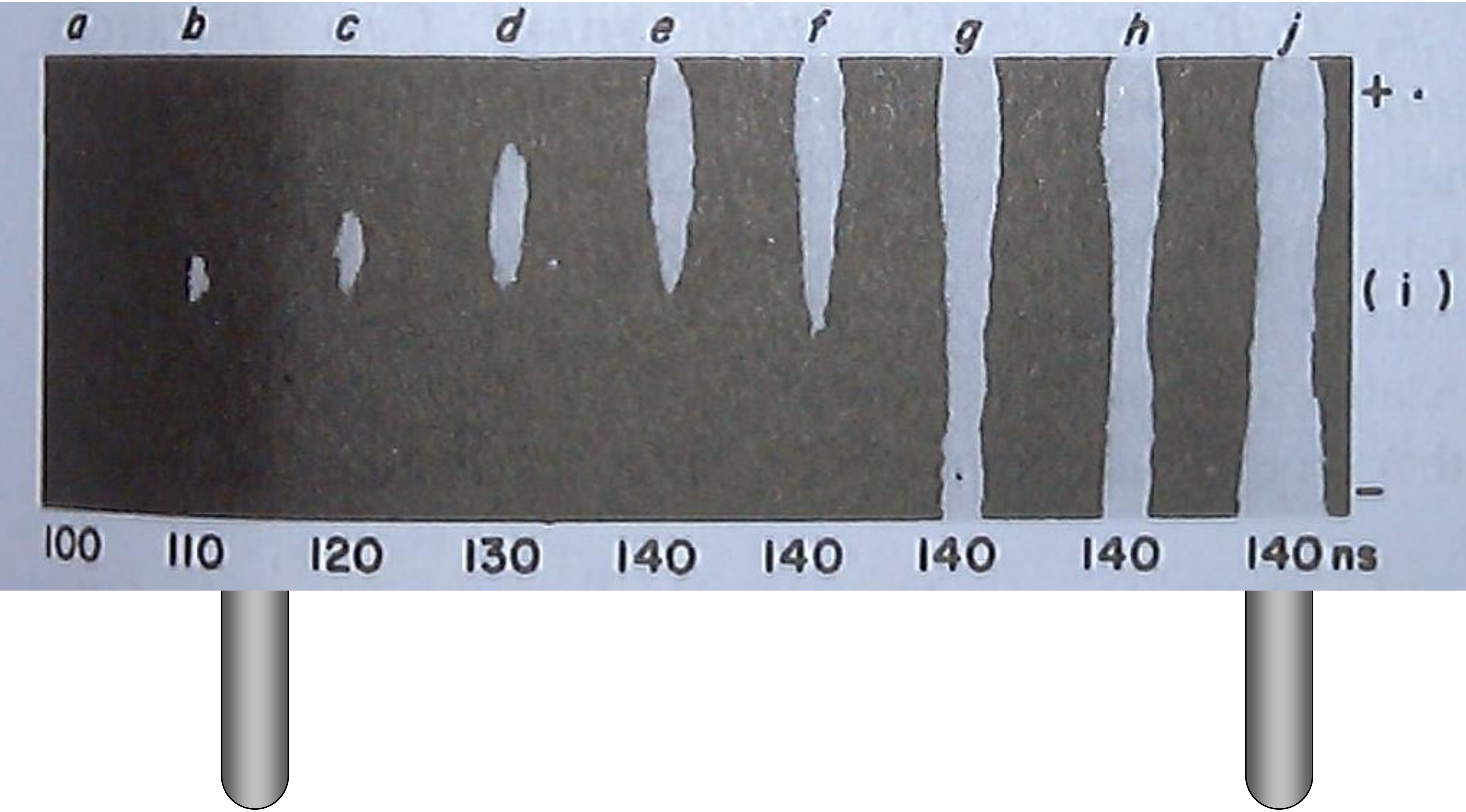


Townsend Secondary Ionisation Coefficient, γ

John Townsend
"Townsend discharge"
1897

$$dn_x = n_x \alpha dx$$

$$n_x = n_0 e^{\alpha x}$$

γ is the number of secondary electrons produced per electron in the primary avalanche

$$\gamma = \gamma_{ion} + \gamma_p + \gamma_m$$

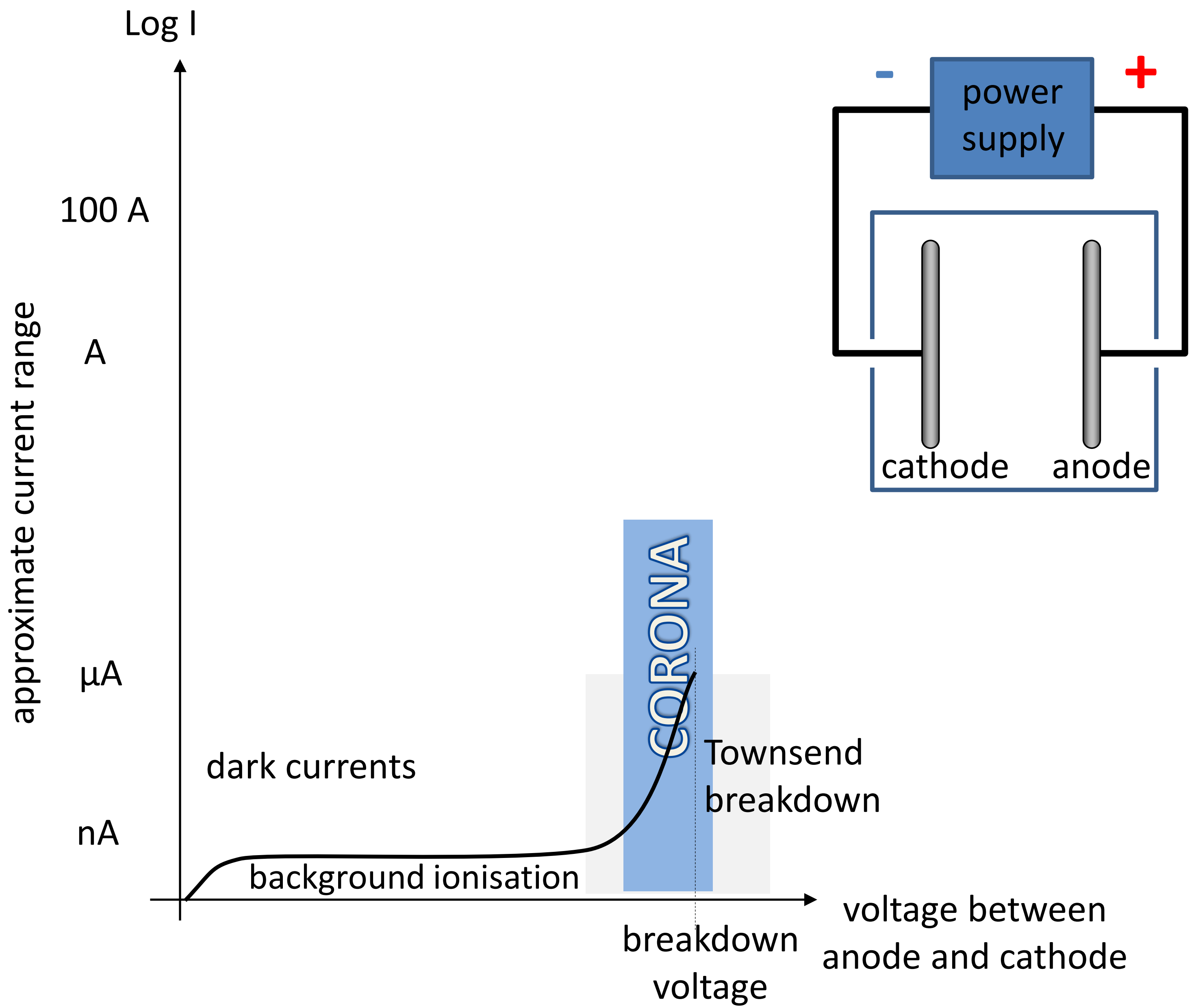
$$I = \frac{I_0 e^{\alpha d}}{1 - \lambda(e^{\alpha d} - 1)}$$

Self sustaining discharge resulting in breakdown when:

$$\gamma e^{\alpha d} = 1$$

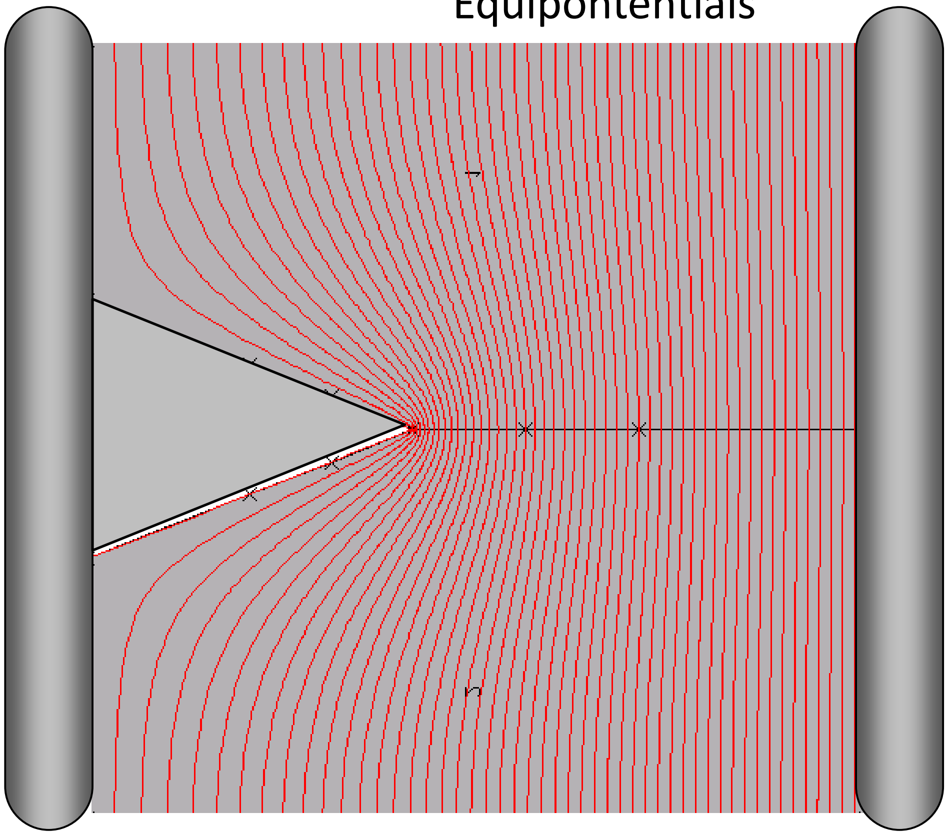
Townsend Criterion for Breakdown

Electrical Discharges



Corona

- Corona is a type of partial discharge occurring in divergent fields
- Divergent fields are caused by sharp points



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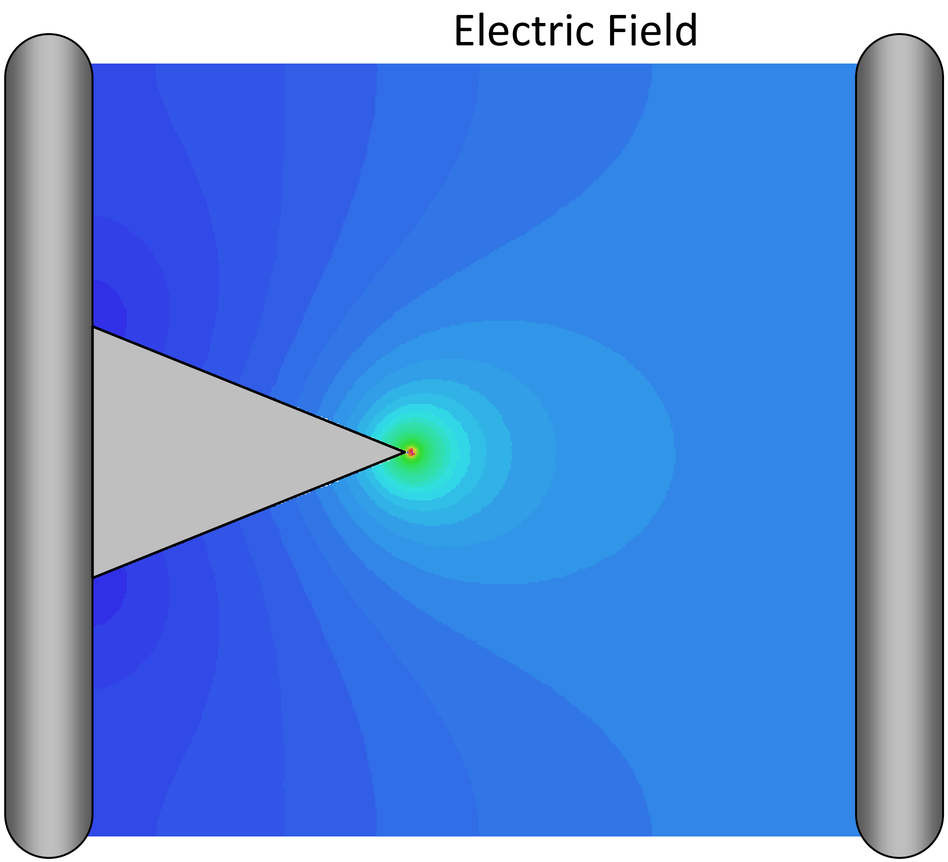
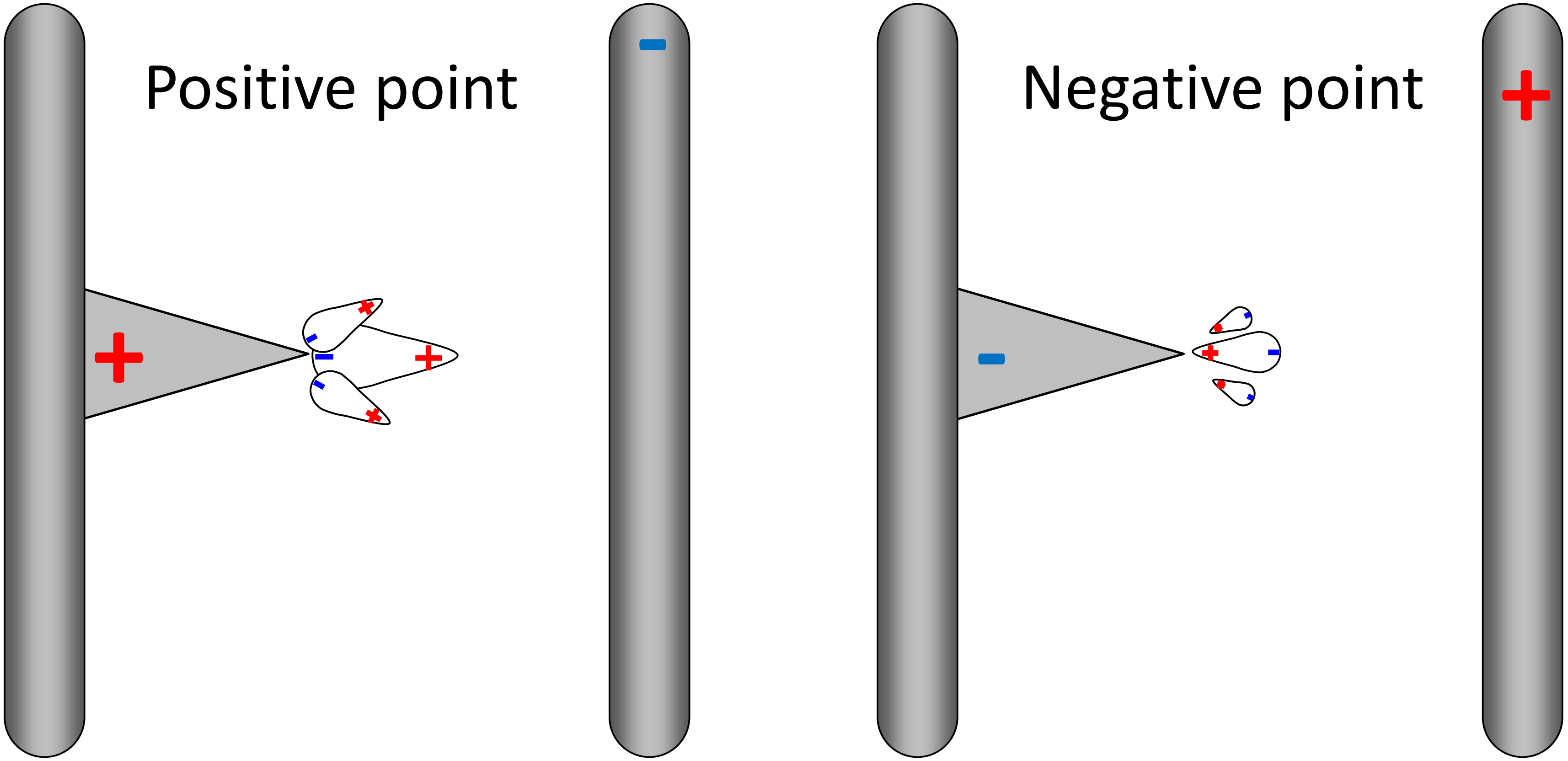


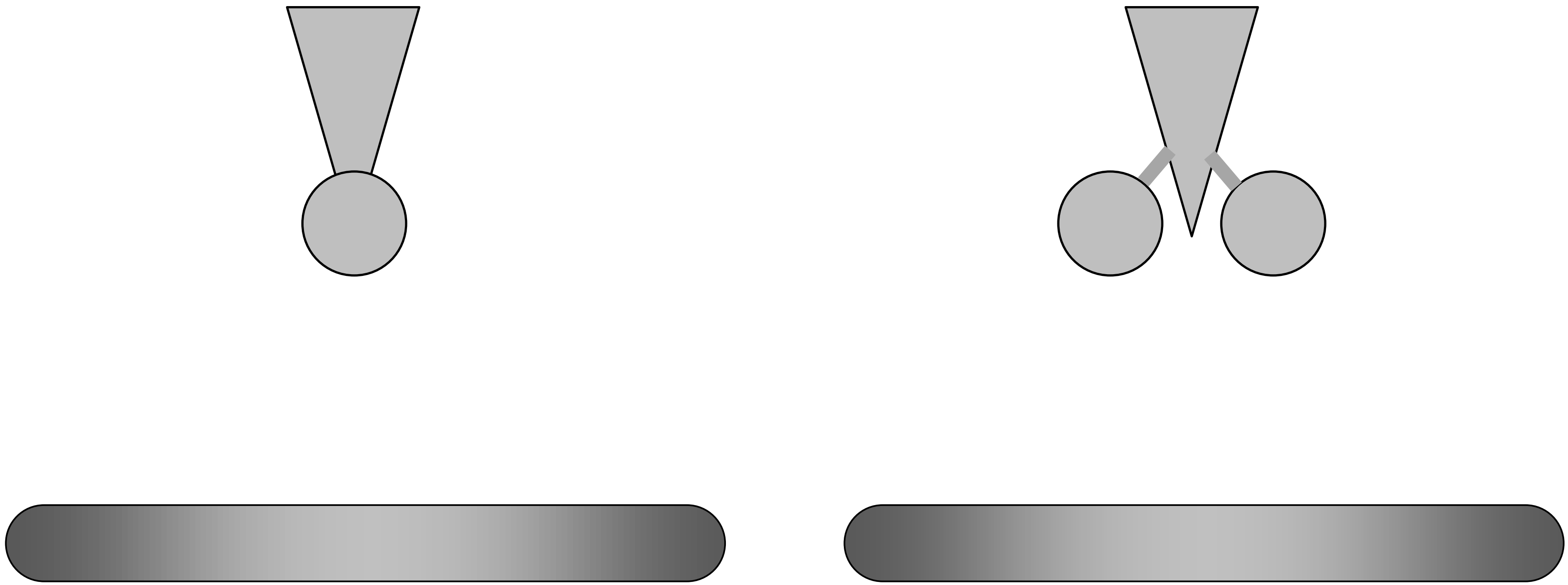
Corona

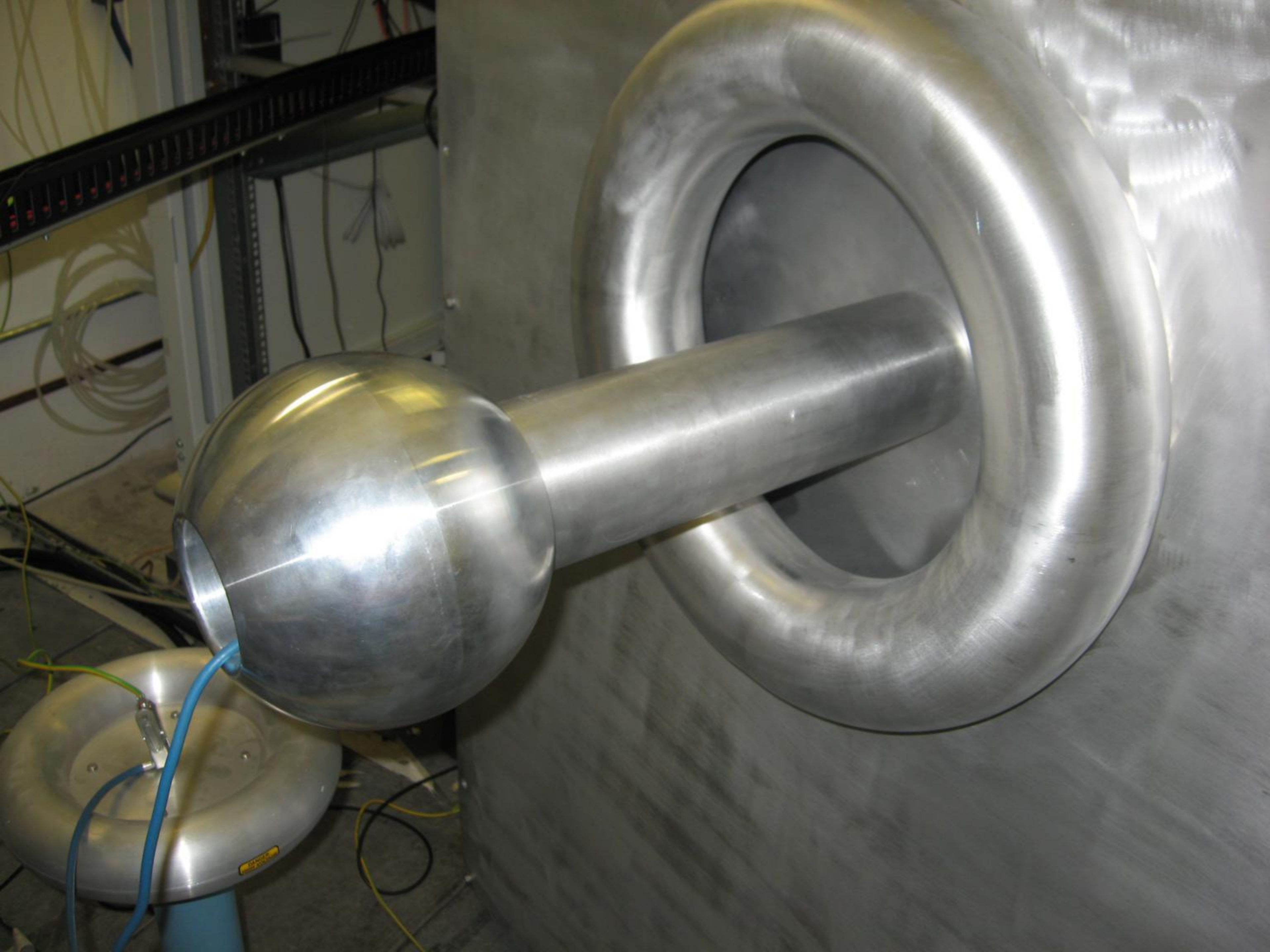
- Corona is a type of partial discharge occurring in divergent fields
- Divergent fields are caused by sharp points
- Discharge behaviour is dependant on polarity



Electrode Design

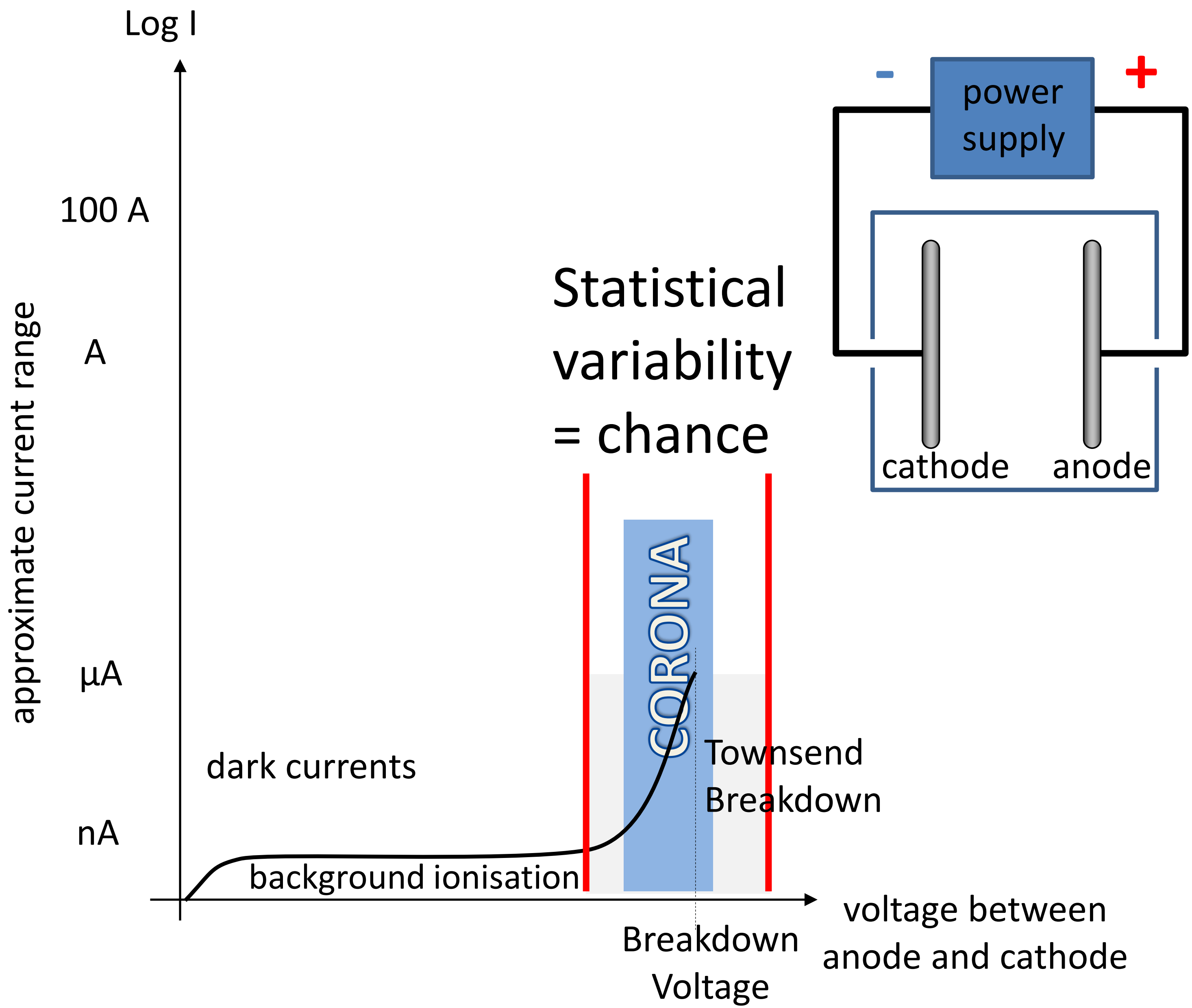
- Minimise Electric Field by making smooth rounded electrodes
- Shield any sharp points with corona shields





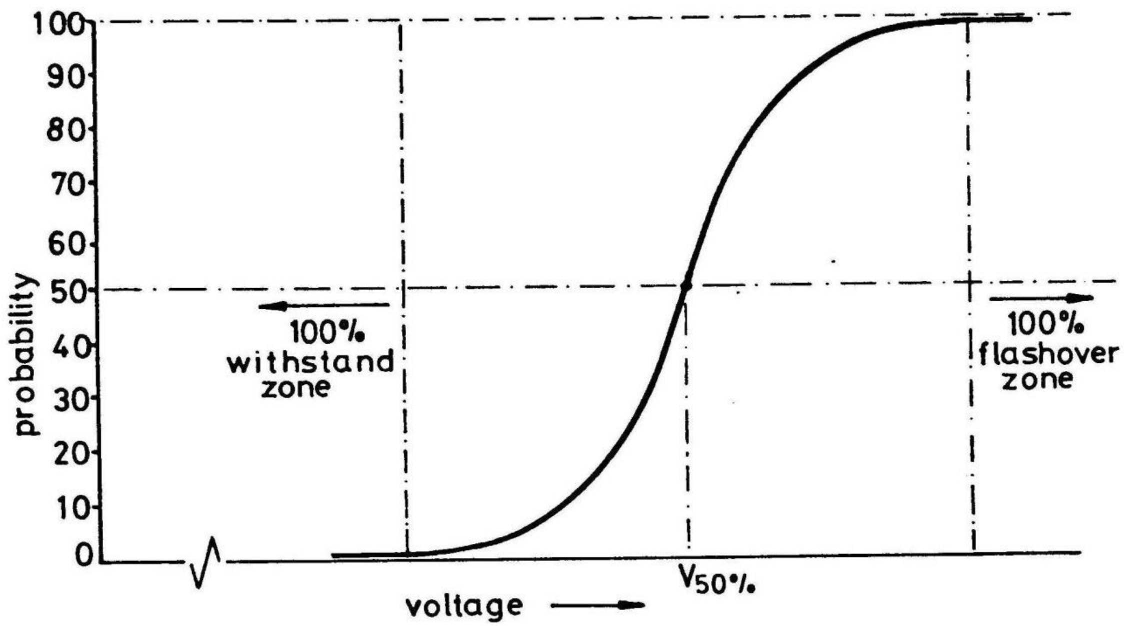

JLG LIFT

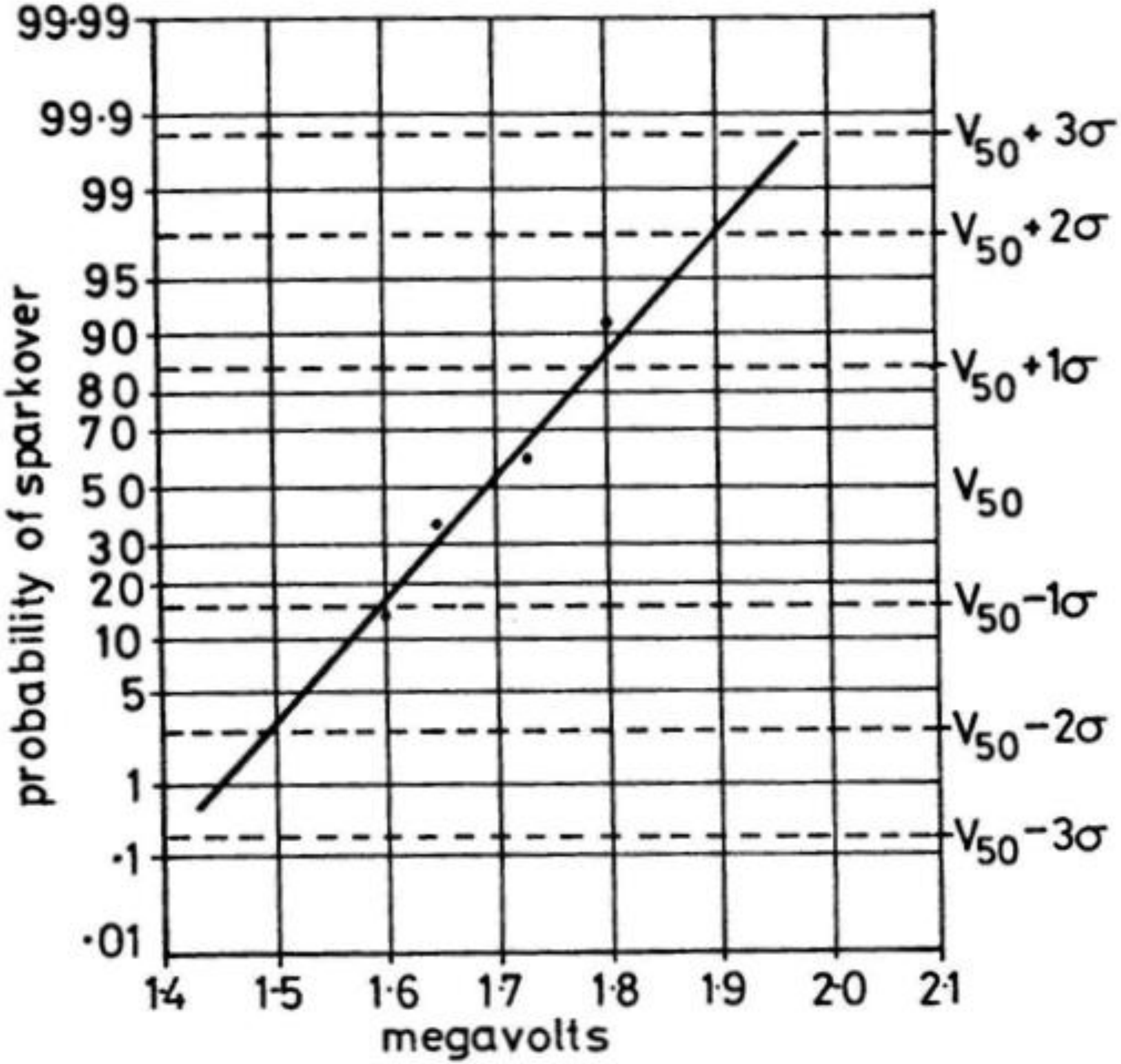
Electrical Discharges



Statistical Variability

Even with identical conditions the same electrode gap will breakdown at different voltages each time the voltage is applied. This is because of the statistical nature of high voltage breakdown: no two sparks are ever the same.





99·99
99·9
99
95
90
80
70
50
30
20
10
5
1
·1
·01
probability of sparkover
$V_{50}+3\sigma$
$V_{50}+2\sigma$
$V_{50}+1\sigma$
V_{50}
$V_{50}-1\sigma$
$V_{50}-2\sigma$
$V_{50}-3\sigma$
1·4
1·5
1·6
1·7
1·8
1·9
2·0
2·1
megavolts

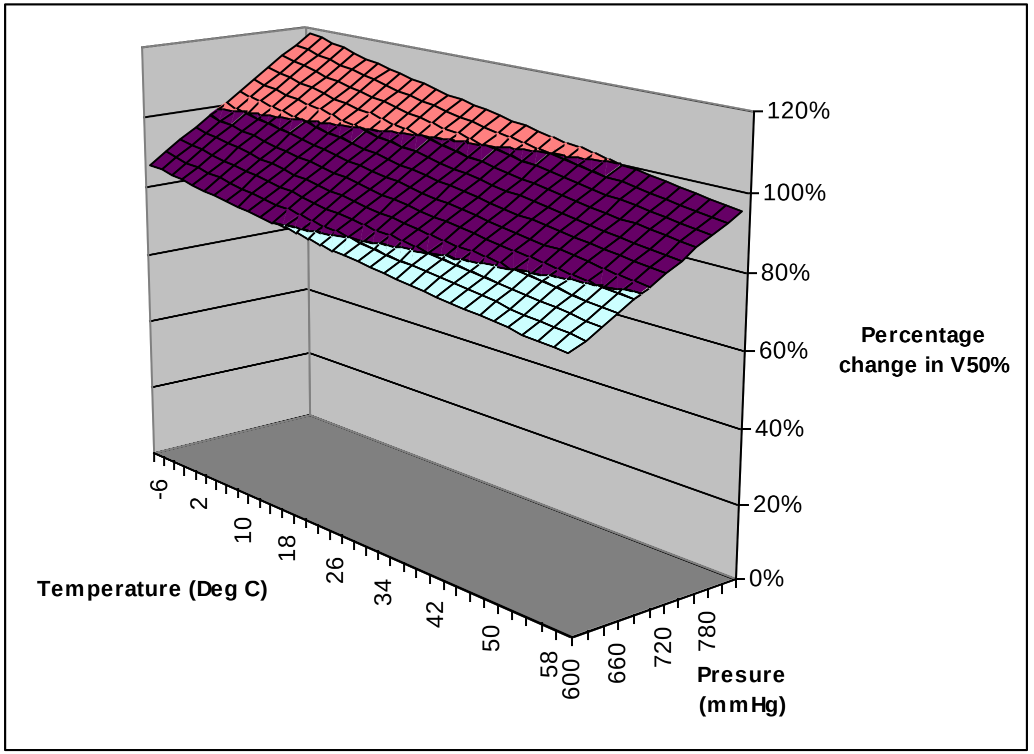
Environmental conditions

Higher temperatures and lower pressures lead to lower flashover voltages. A correction factor for V50% can be found from this equation:

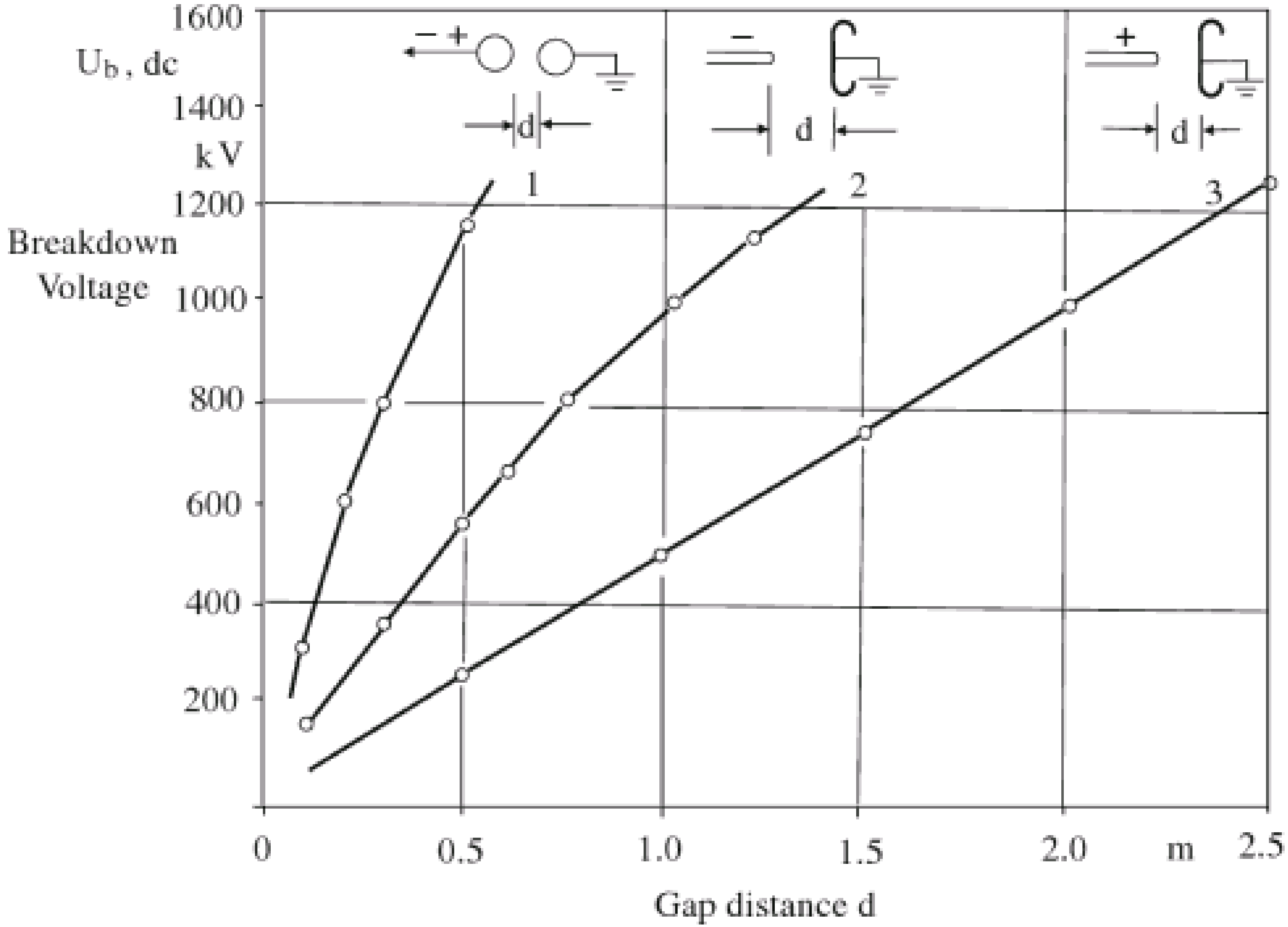
$$\frac{0.386 \times P}{273 + t}$$

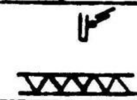
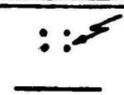
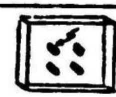
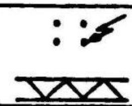
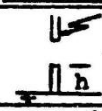
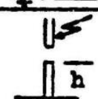
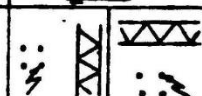
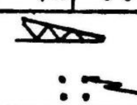
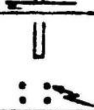
where P is in mmHg and t is in degrees centigrade.

Humidity can also affect breakdown voltage



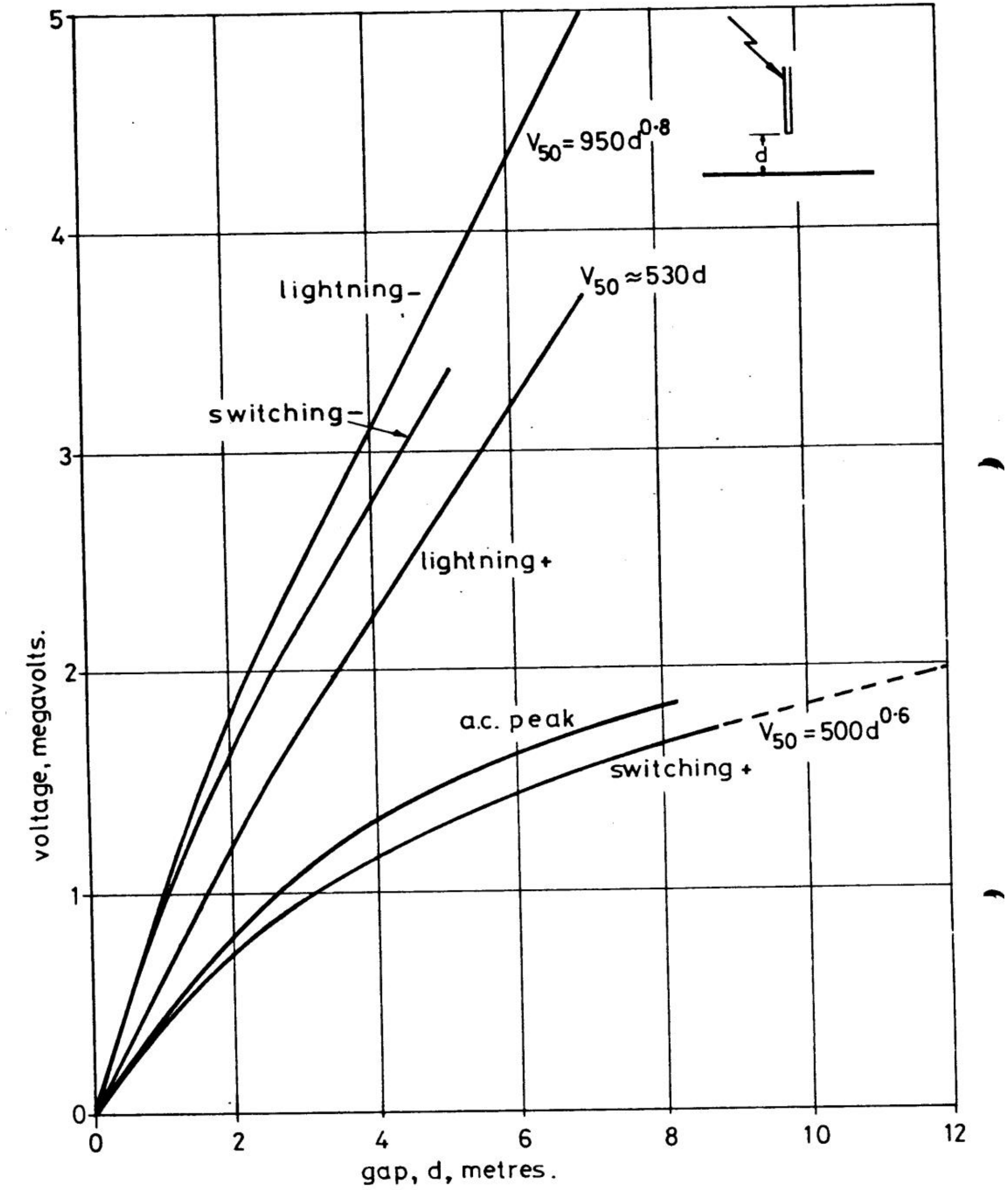
Polarity is important in Non Uniform Gaps



	Gap.		"K"
1.	Rod-plane.		1.00
2.	Rod-structure.		1.05
3.	Conductor-plane.		1.15
4.	Conductor-window.		1.20
5.	Conductor-structure.		1.30
6.	Rod-rod (h=3m;under)		1.30
7.	Rod-rod (h=6m;under)		1.40
8.	Conductor-structure, (over &laterally)		1.39
9.	Conductor-crossarm end		1.55
10.	Conductor-rod (h=3m;under)		1.65
11.	Conductor-rod (h=6m;under)		1.90
12.	Conductor-rod (over)		1.90
13.	Conductor rod		1.40

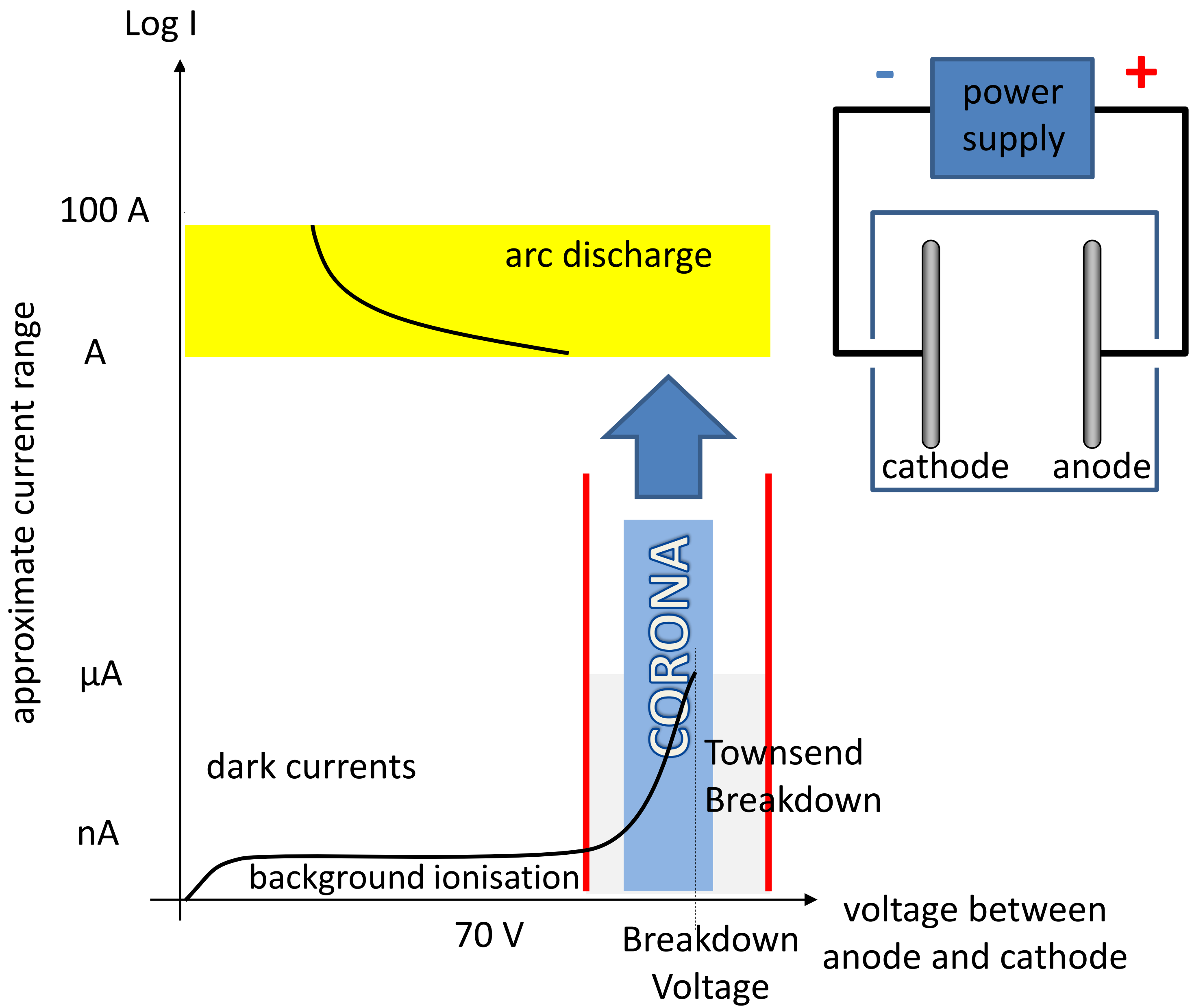
Geometry Scaling factors

Type of Applied Voltage is Important



Electrical Discharges

Dependant on power supply and what is between electrodes



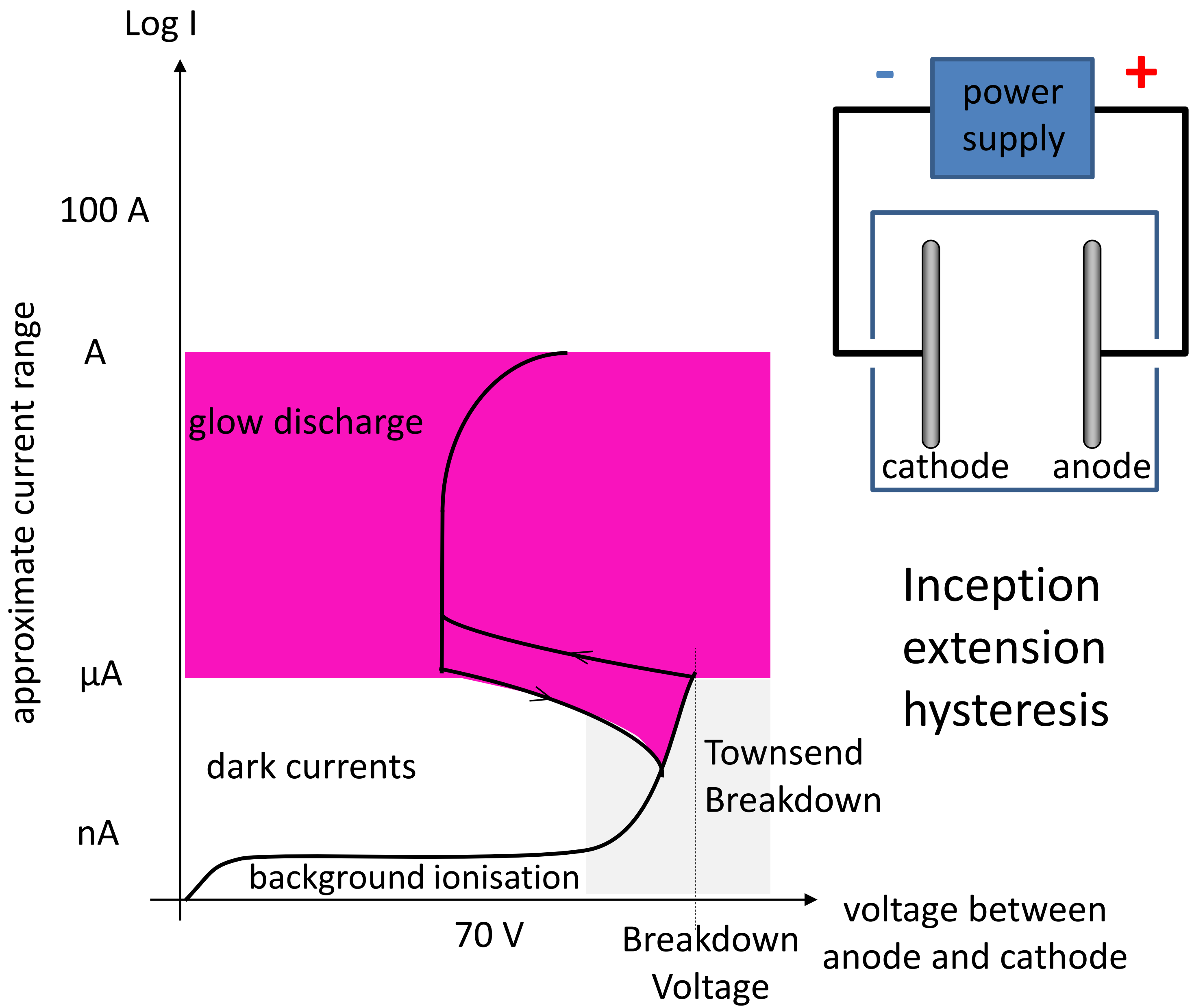
Arcs

Bad

Good

Electrical Discharges

If the pressure is low enough

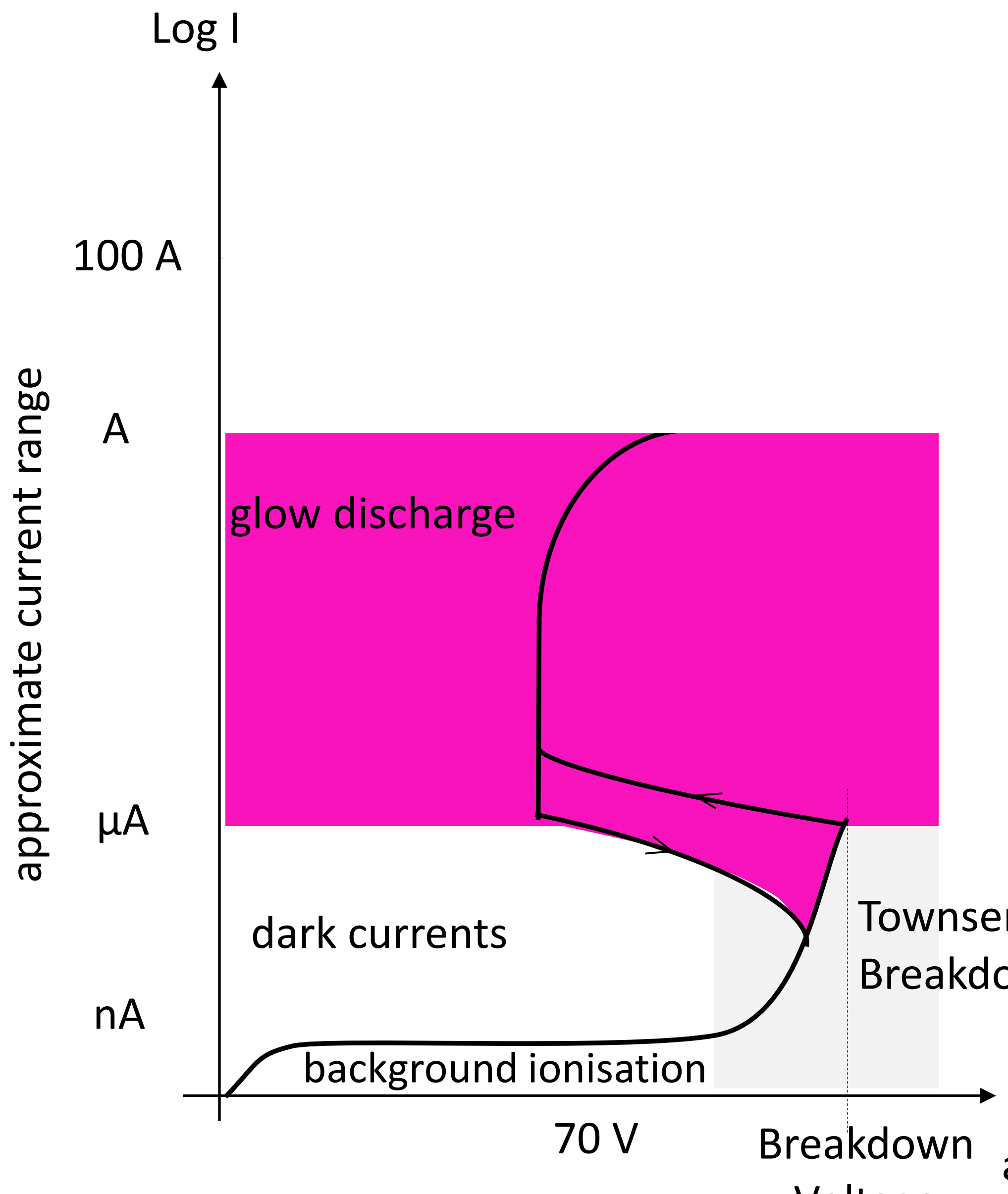


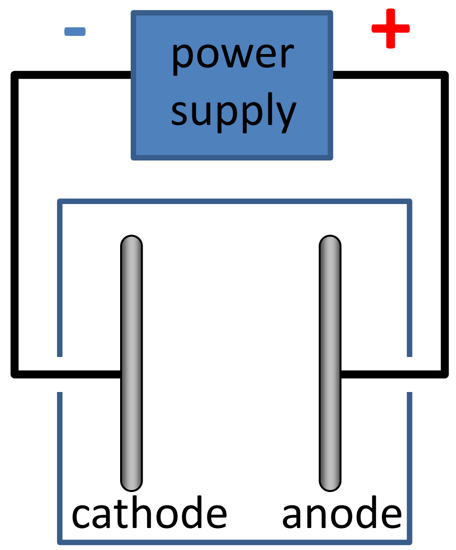
Inception
extension
hysteresis


BANG
BANG

Electrical Discharges

If the pressure is low enough

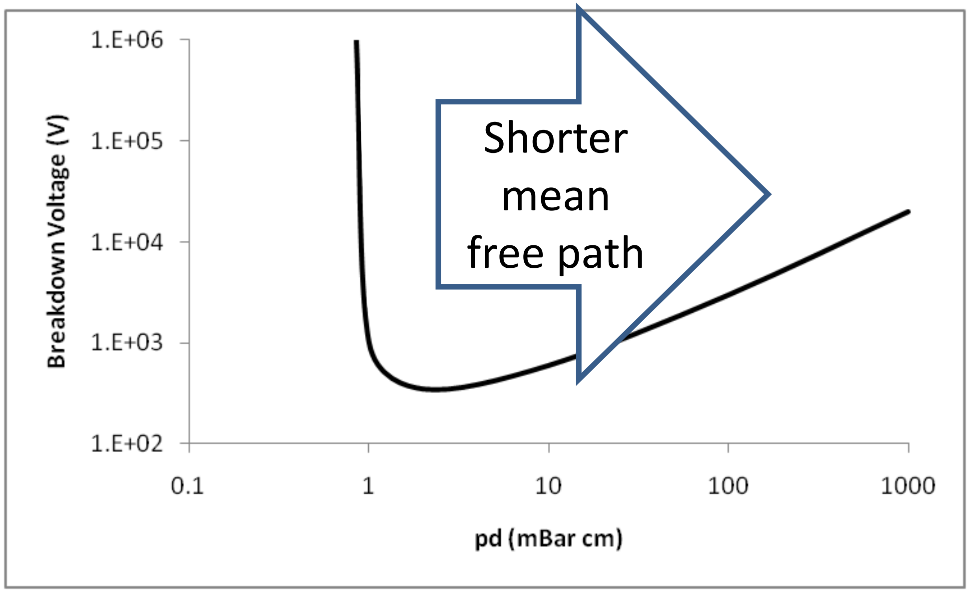




Inception
extension
hysteresis

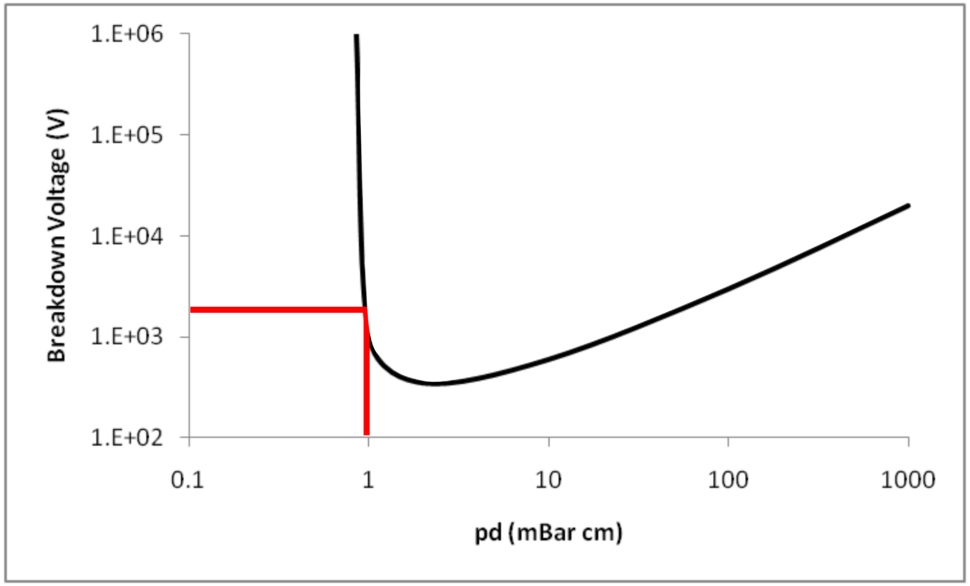
Paschen Curve

Friedrich Paschen 1889



Paschen Curve

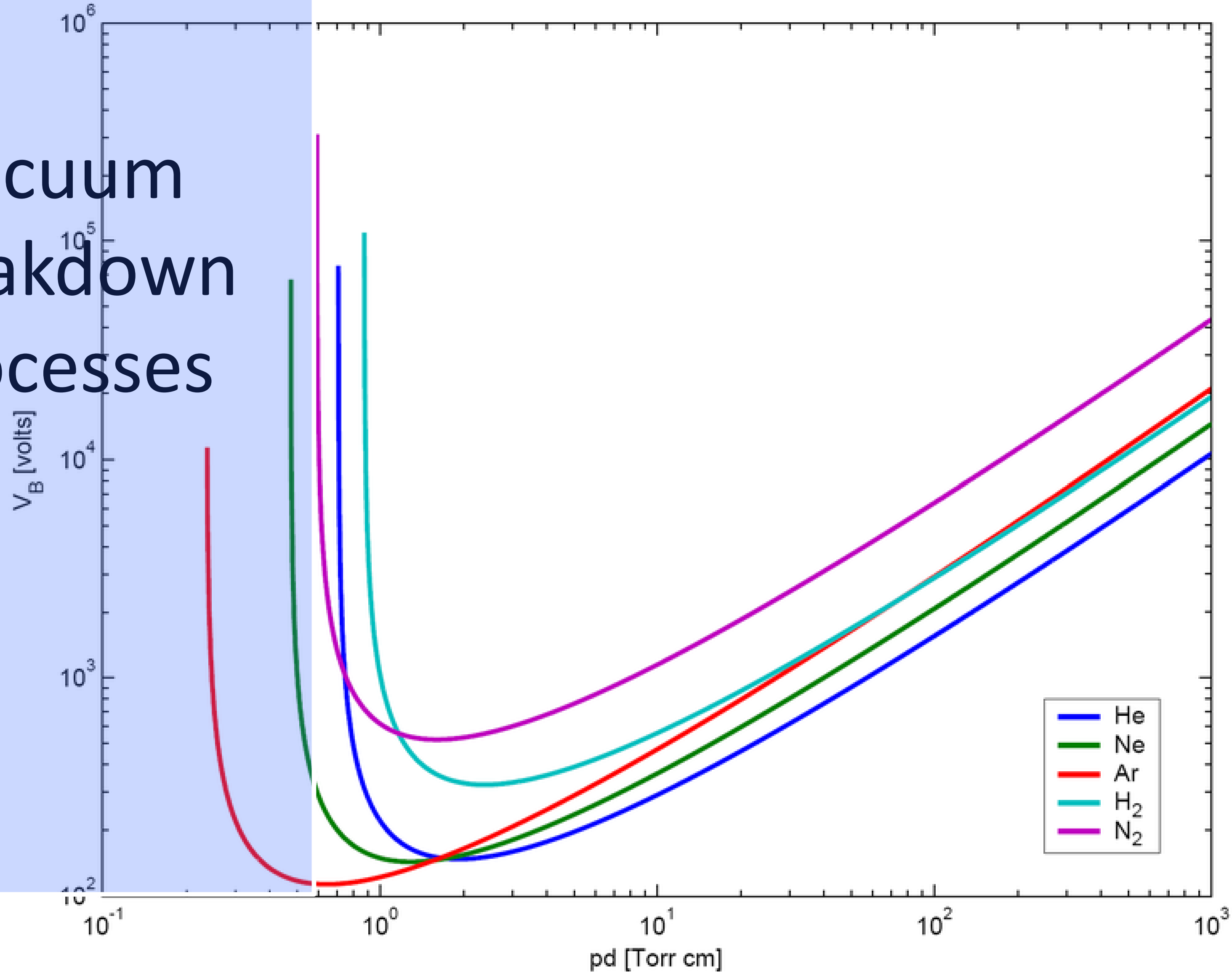
Friedrich Paschen 1889



Operating just below the Paschen Minimum:

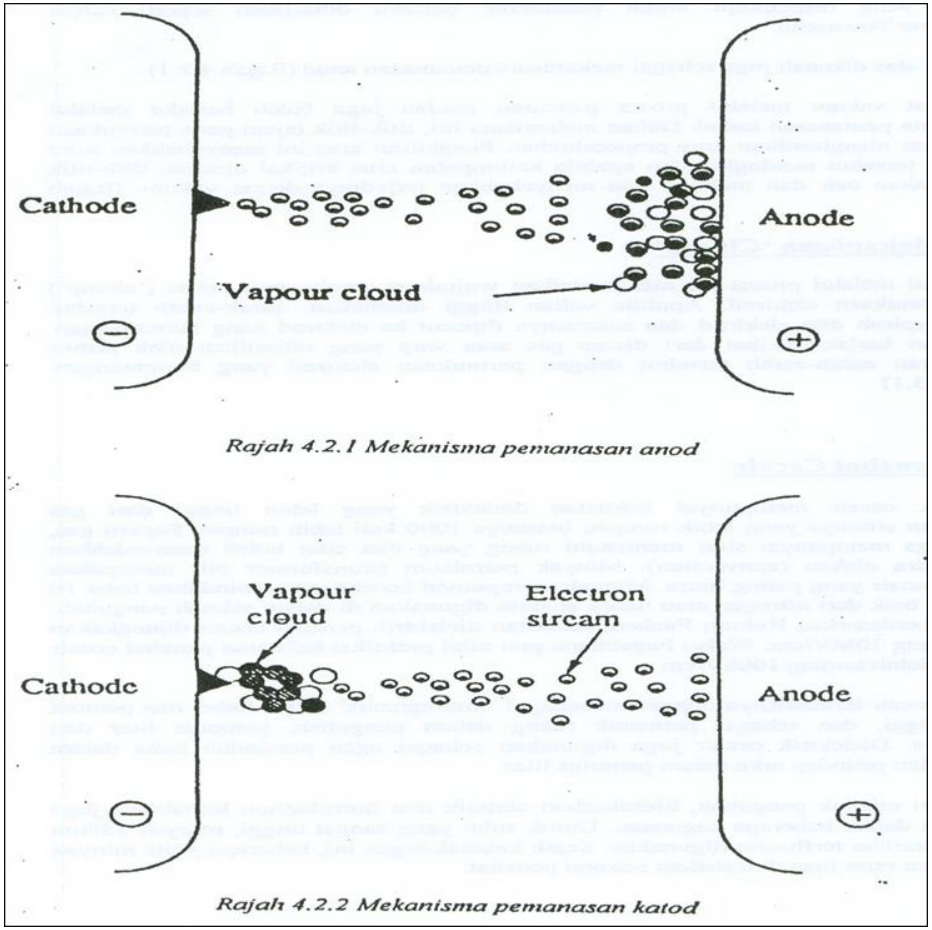
Longer gaps have
lower breakdown voltages!

Vacuum Breakdown Processes



Vacuum Breakdown

Insulating micro-inclusions can also cause field enhancement



Conducting particles from anode

Conducting particles from cathode

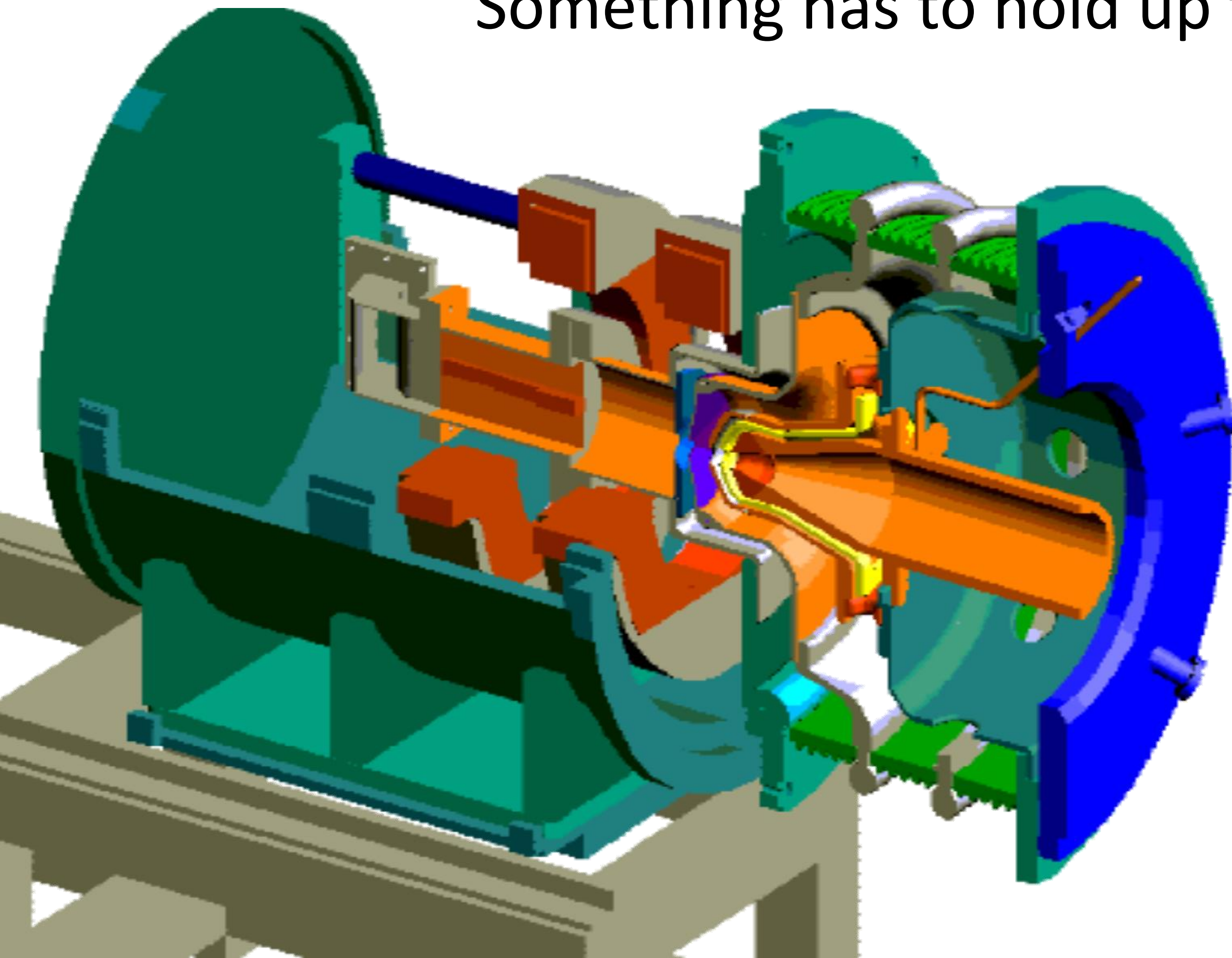
Breakdown strength of Air

In air at normal room conditions two electrodes require about 30 kV for each cm of spacing to breakdown (as a rule of thumb)

Or 3 $kVmm^{-1}$

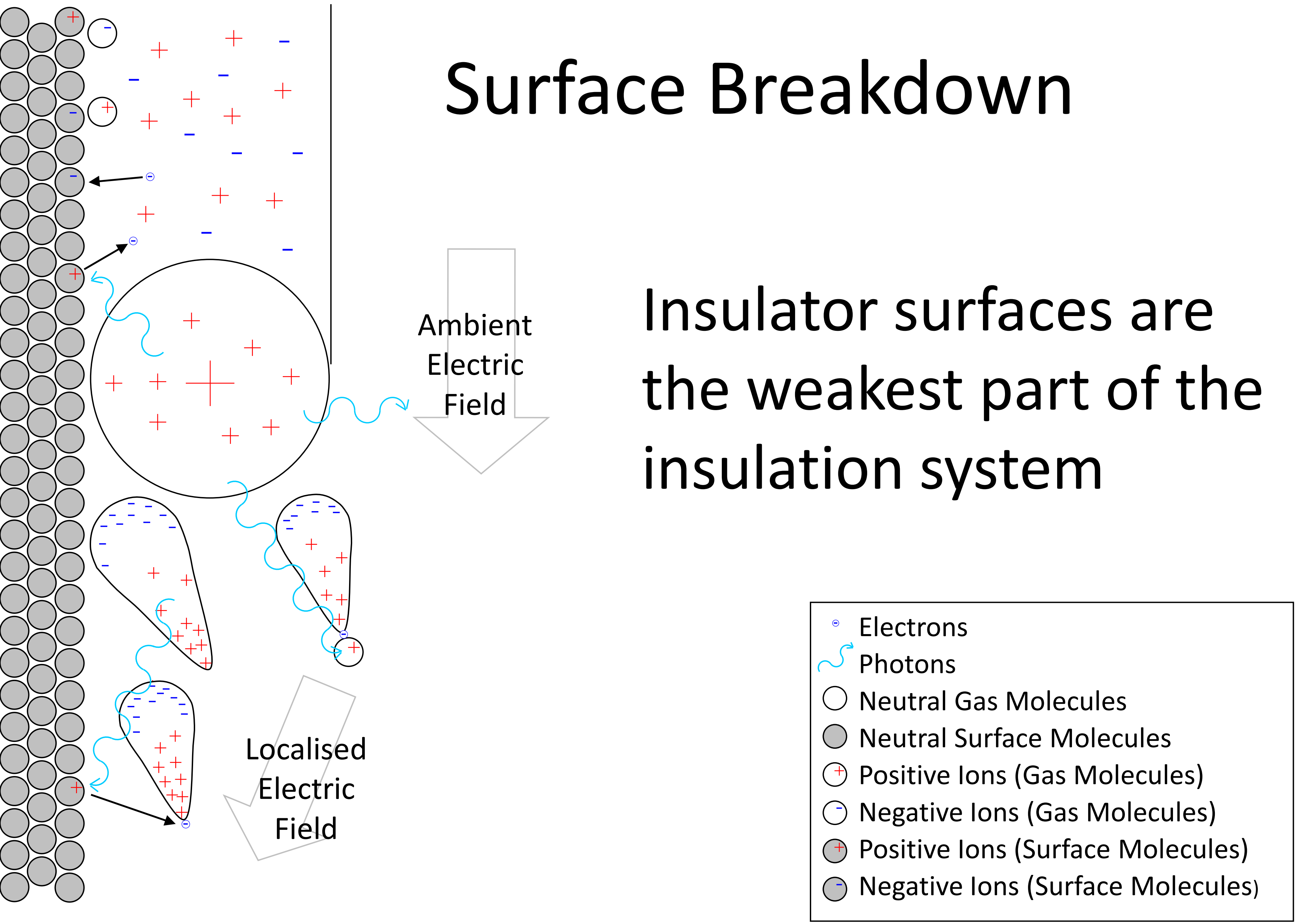
Insulators

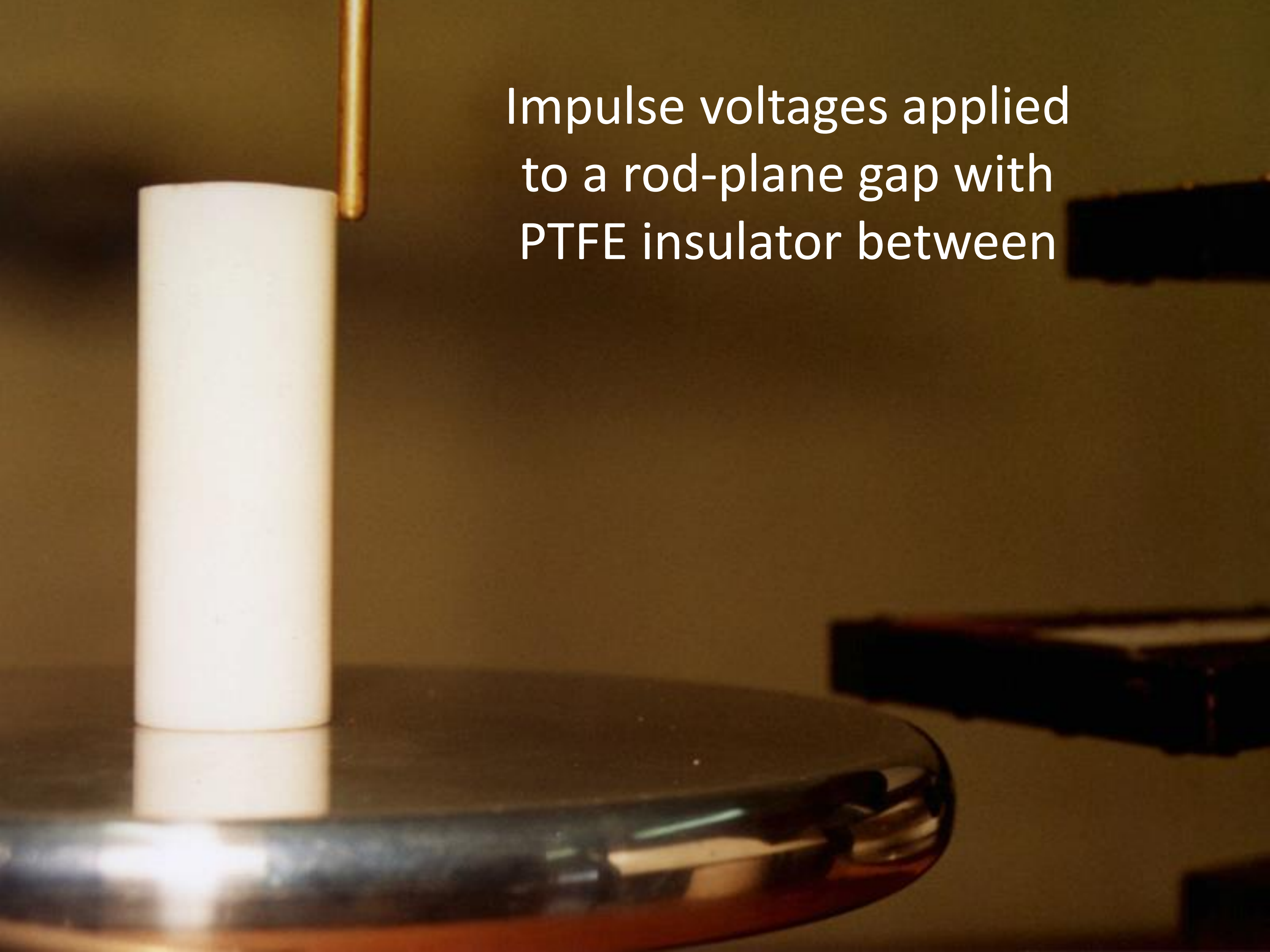
Something has to hold up the electrodes



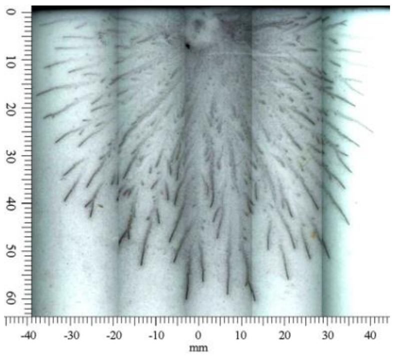
Surface Breakdown

Insulator surfaces are the weakest part of the insulation system

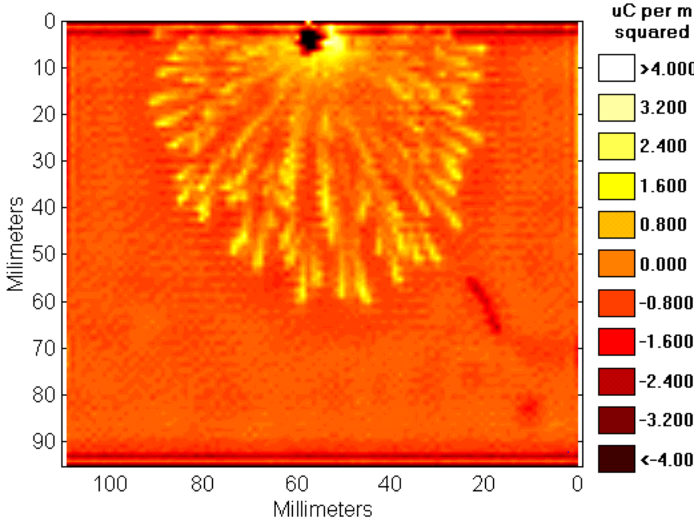



Impulse voltages applied
to a rod-plane gap with
PTFE insulator between

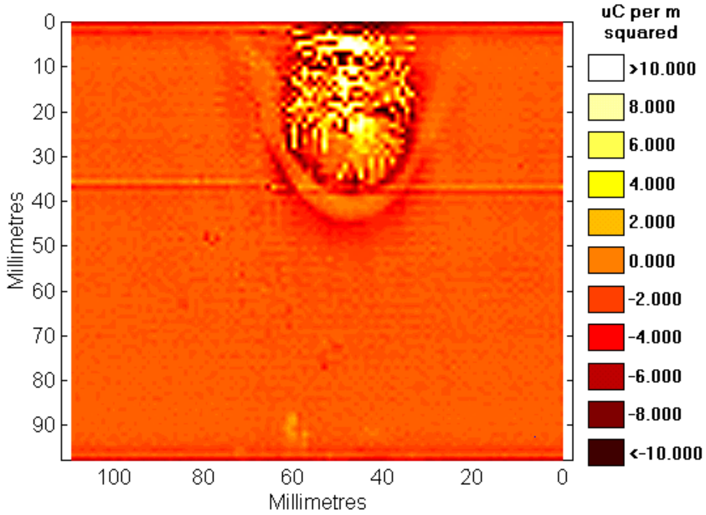
Surface Charging



Dust Figure



Charge Distribution



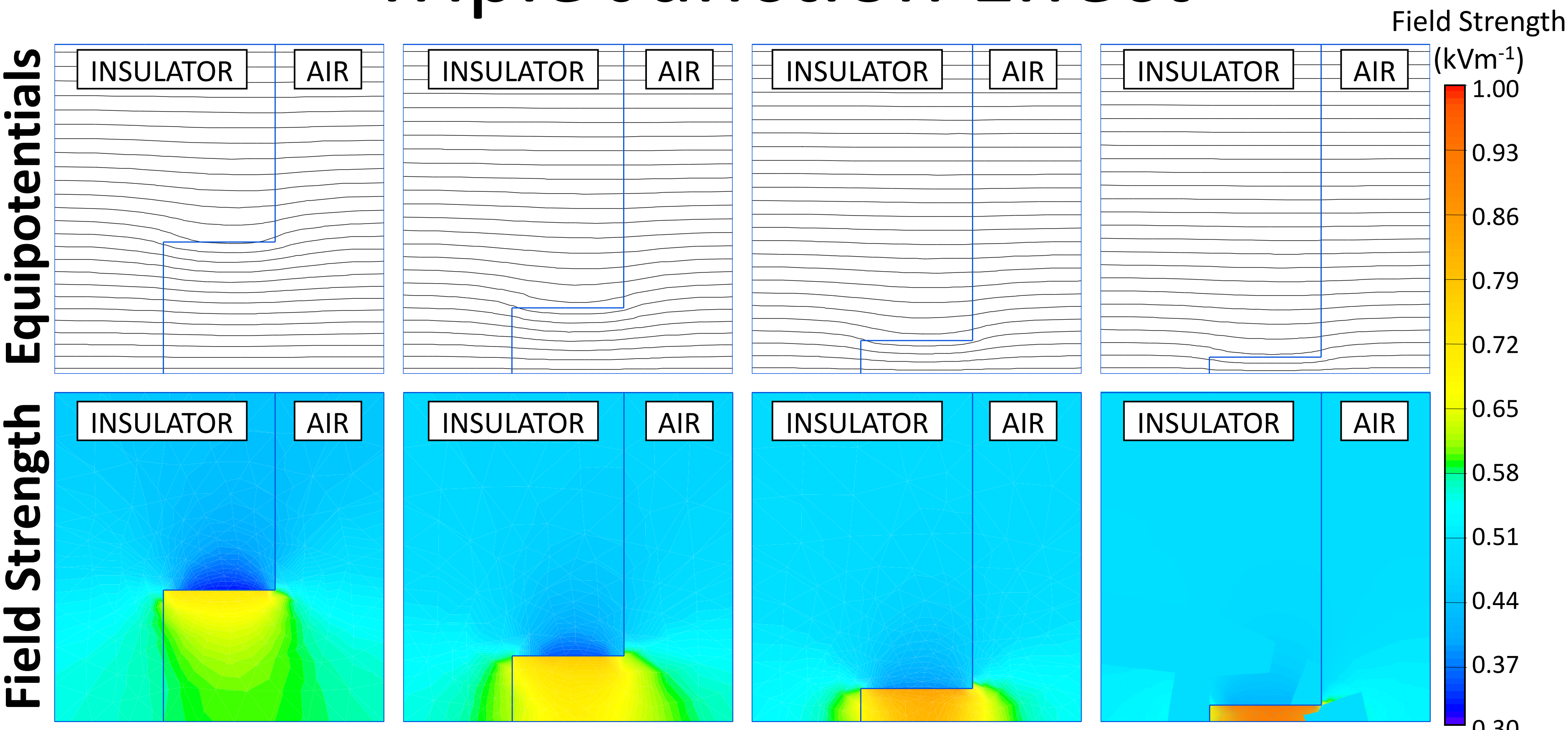
Charge Distribution

+36 kV Impulse

-70 kV Impulse

Polarity is very important if the gap is asymmetrical

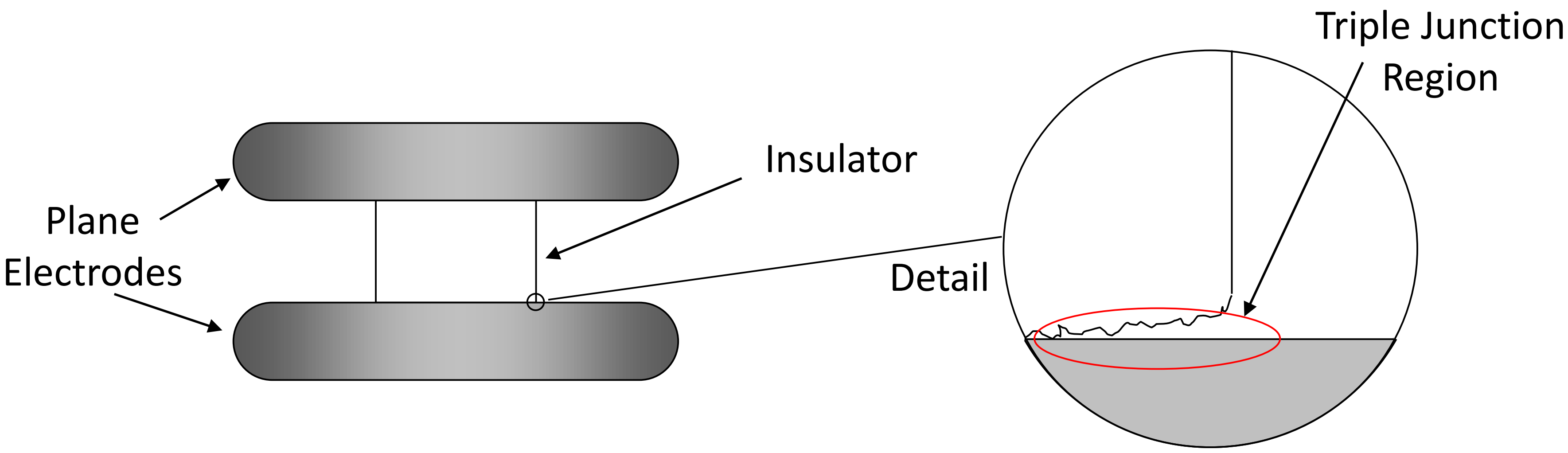
Triple Junction Effect



4mm Triple Junction | *2mm Triple Junction* | *1mm Triple Junction* | *0.5mm Triple Junction*

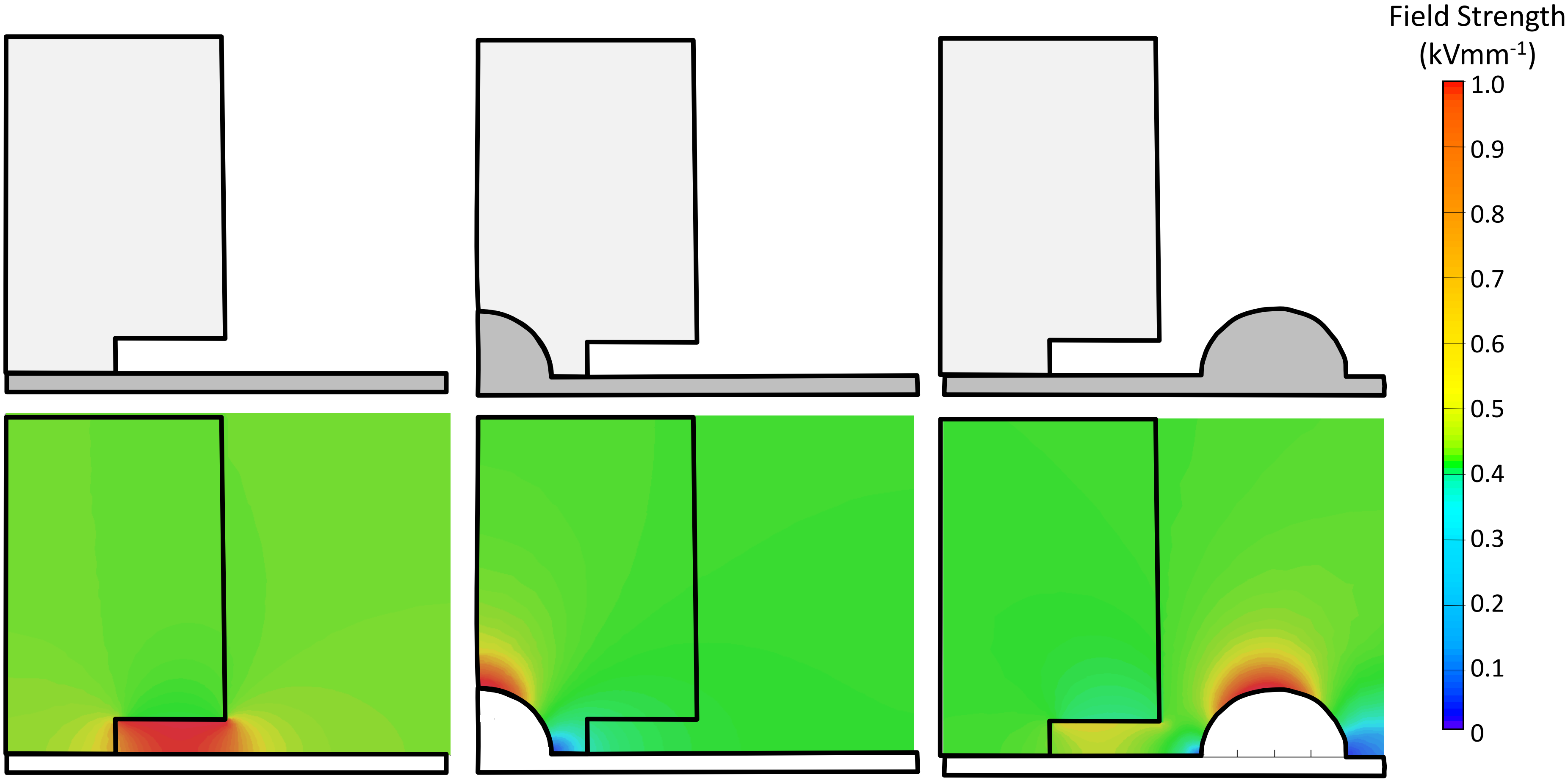
PTFE (ε_r = 2.2) ambient field of 0.5 kVmm^{-1}

Triple junctions always exist at some scale



Triple Junction Screening

1 mm PTFE triple junction ambient field of 0.5 kVm^{-1}



No Screening

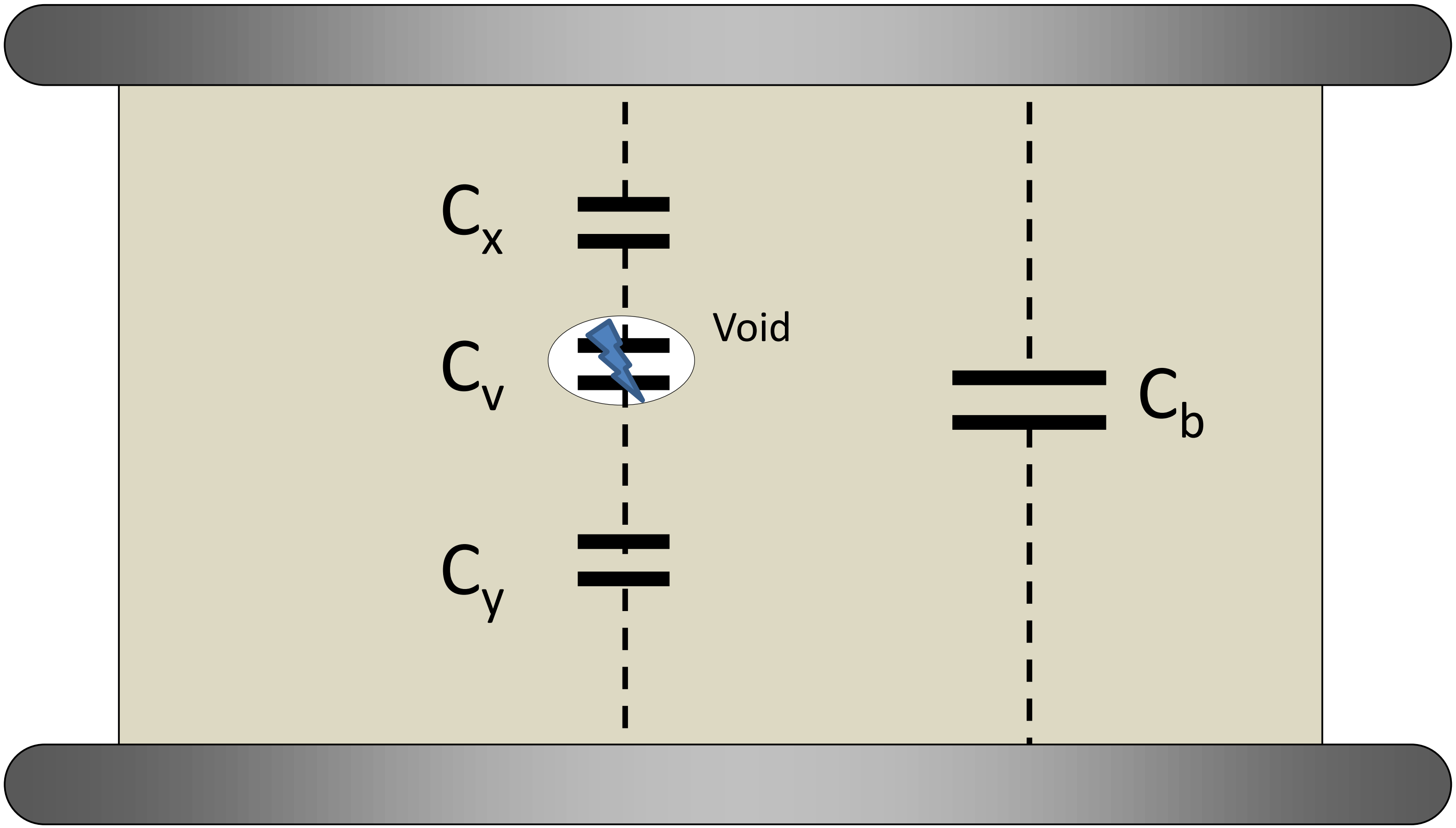
Inside Insulator

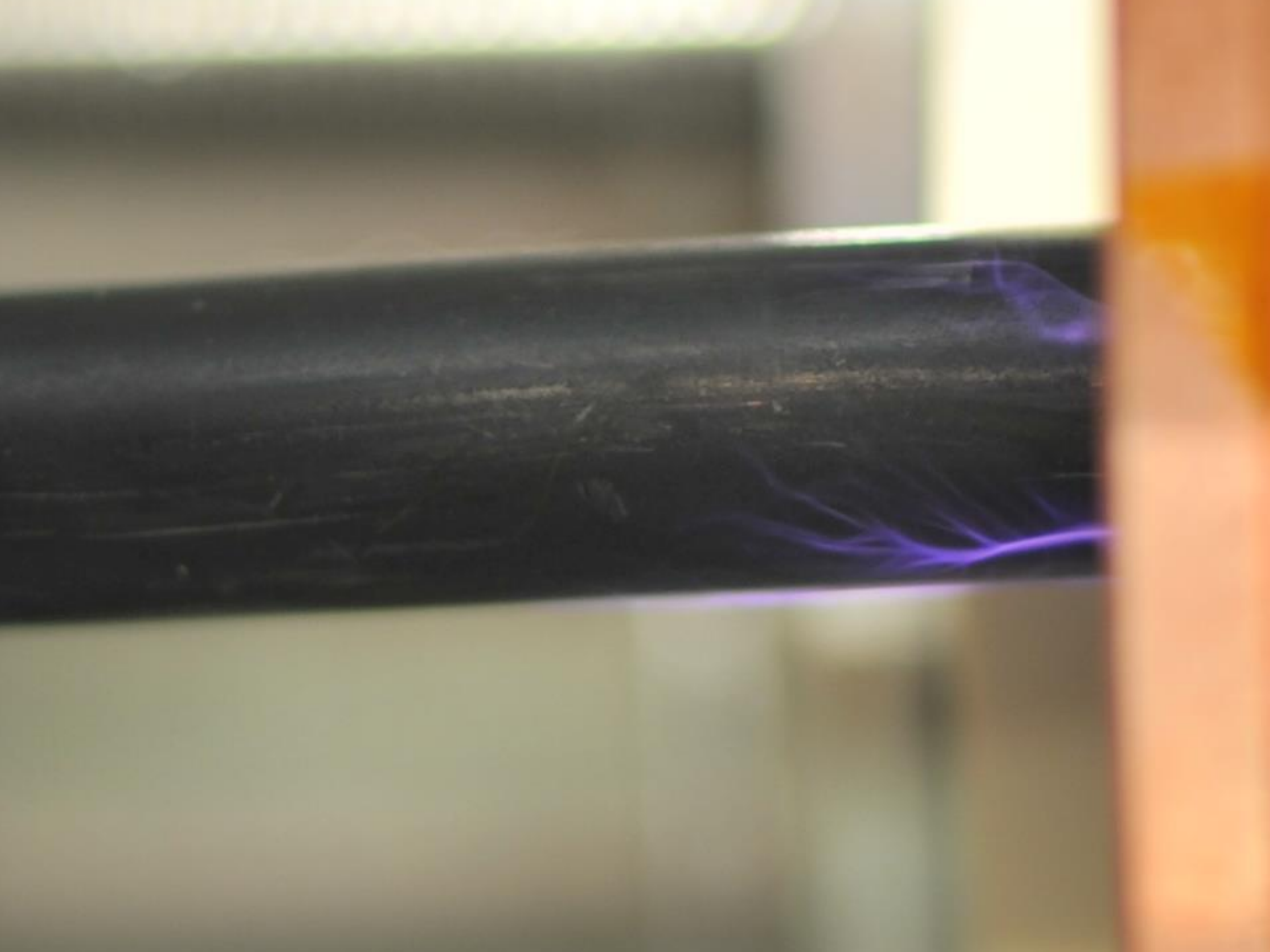
Outside Ring

Electrical Breakdown

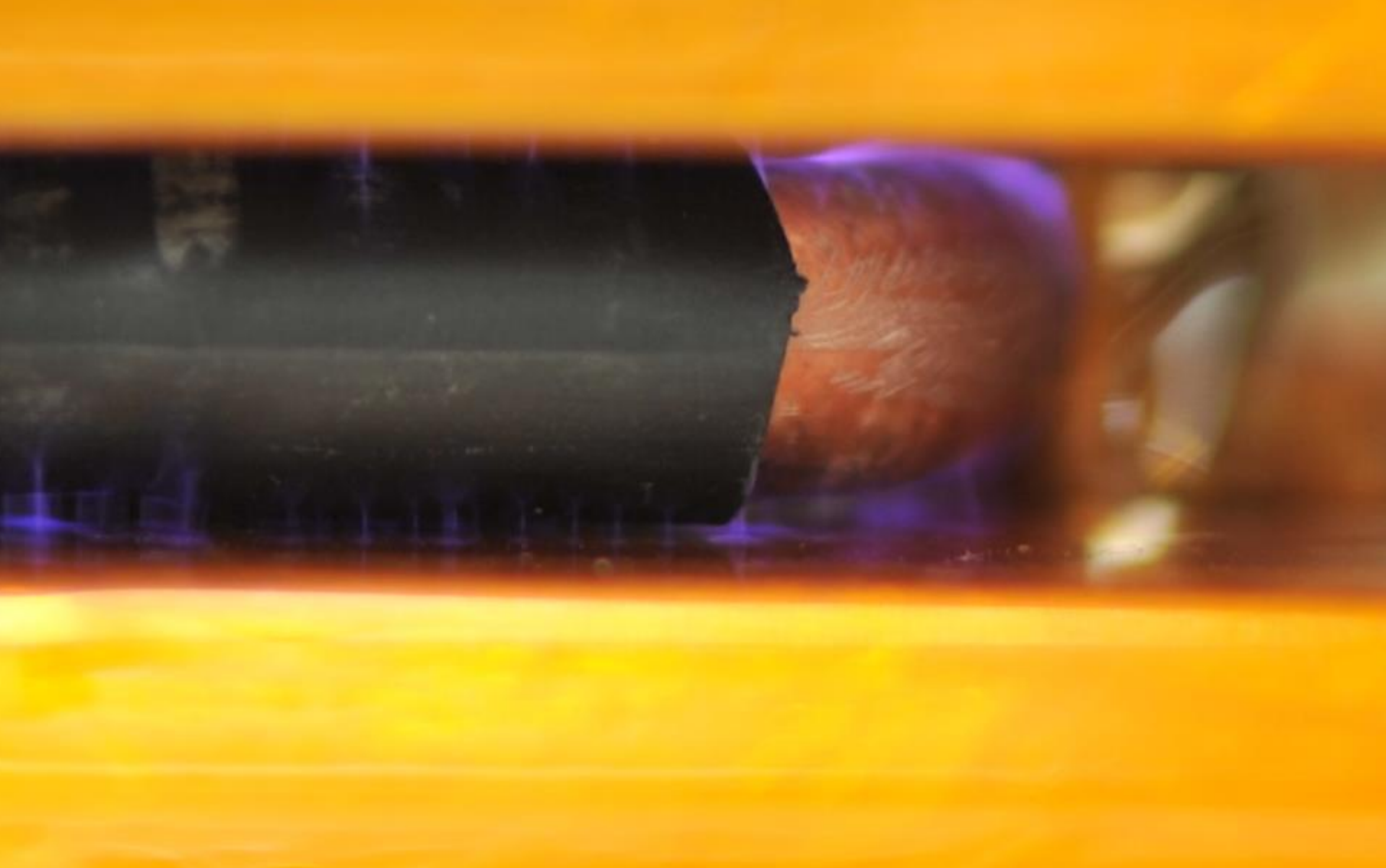
- Global Breakdown
  - Complete rupture or failure of the insulation between two electrodes
- Local Breakdown
  - Partial breakdown of part of the insulation between two electrodes

Partial Discharges

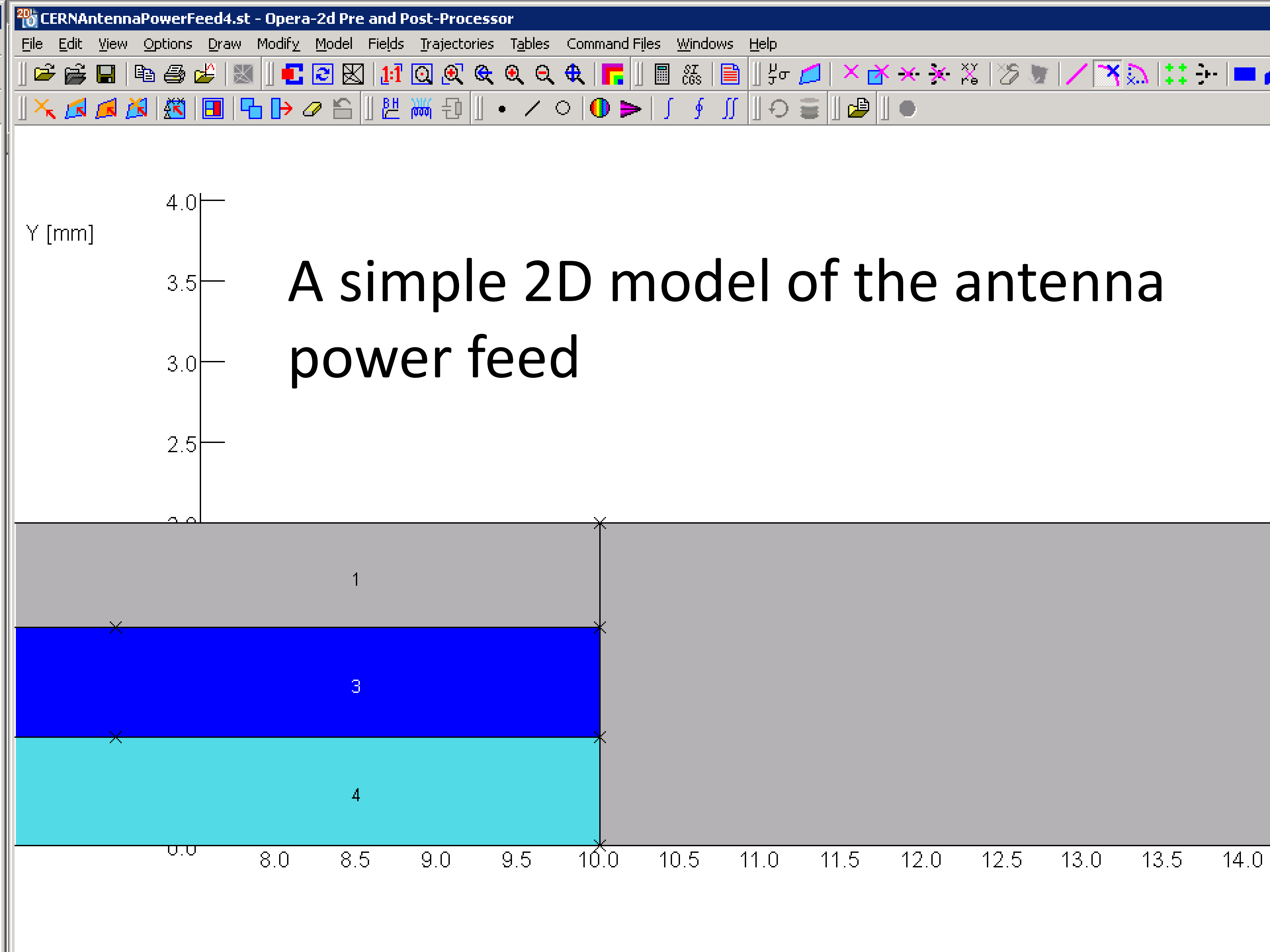




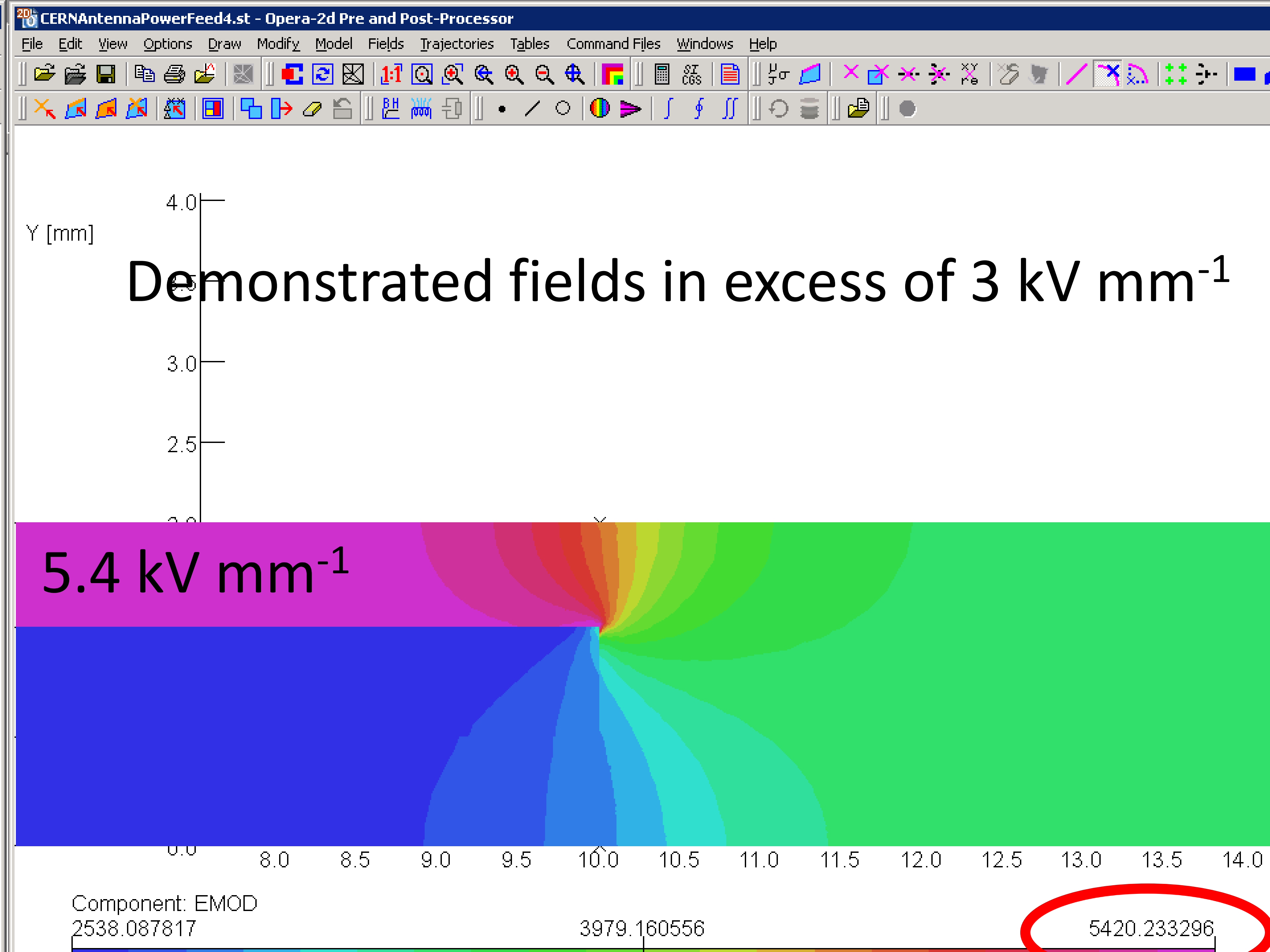
Antenna power feed sparking



A simple 2D model of the antenna power feed



Demonstrated fields in excess of 3 kV mm^{-1}



Insulator Materials

Depends on application!

For example:

Al_2O_3 is commonly used in vacuum

AlN is used when a high thermal conductivity is required

Macor is used when a complex shape needs to be machined

Porcelain is used in compression

Epoxy resin is used to impregnate and pot

Mica is used for thin high voltage withstand

Glass is used when visible transparency is required

XLPE is used for extrusion in cables

Rexolite is used for high frequency RF

Commercial Insulators

- Dirt, dust and waterproof
- Sheds increase tracking length and protect sections of surface

A well designed insulation system is one you don't ever have to worry about

High voltage platforms don’t have to be too complicated, but...

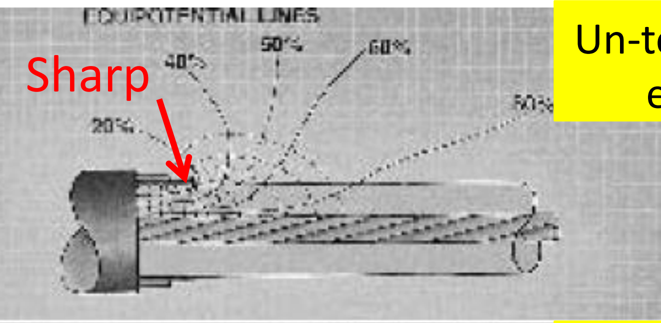
Water and home-made insulators don’t mix


XL

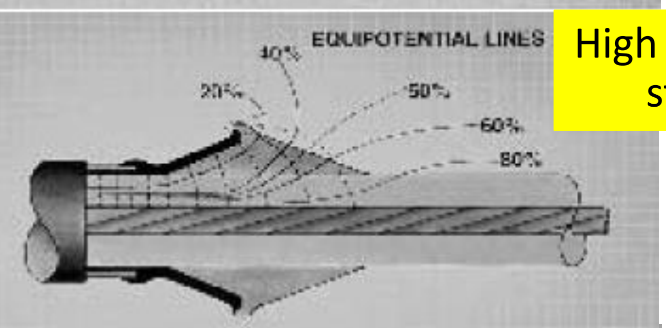
Commercial insulators are relatively cheap (≈€200) and will work in all conditions

Cable terminations

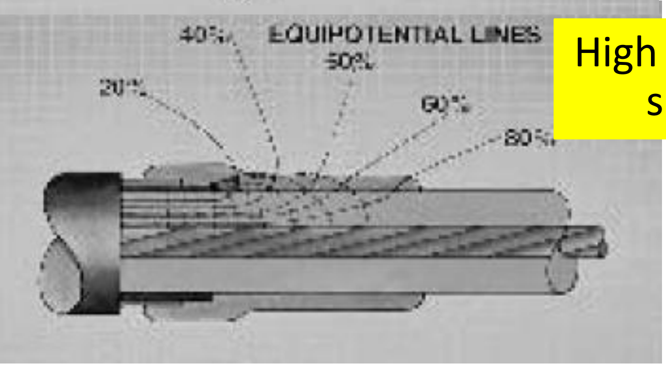
Correct electrostatic termination of high voltage cables is essential



Un-terminated earth screen



High permittivty stress cone



High permittivty sleeve

Stress cone electrode

Correct impedance termination of pulsed cables is also important – voltage reflections

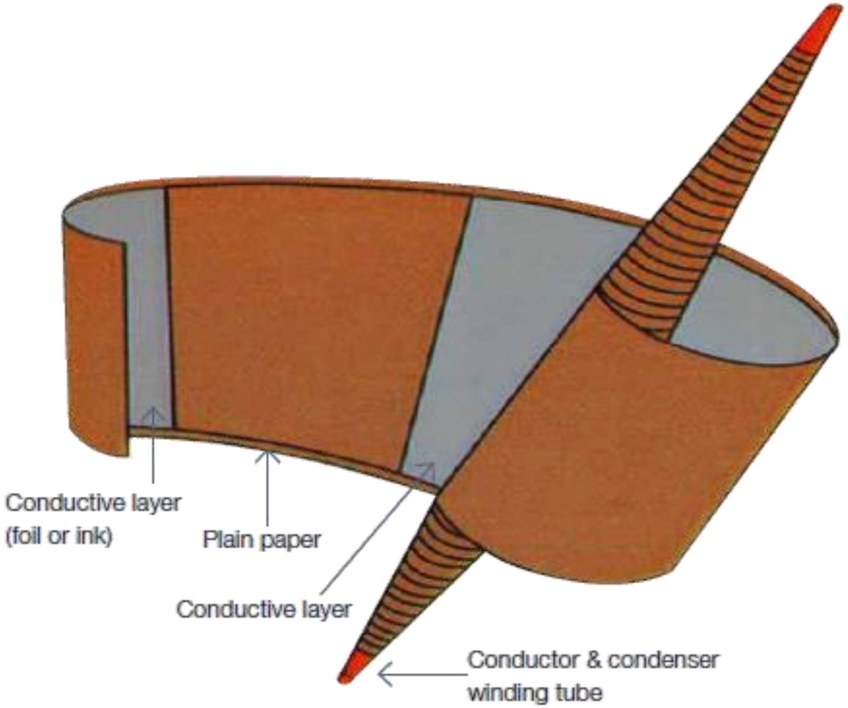
Connectors and Feedthroughs

Depends on...

- Application
- Maintenance
- Permanence
- Voltage

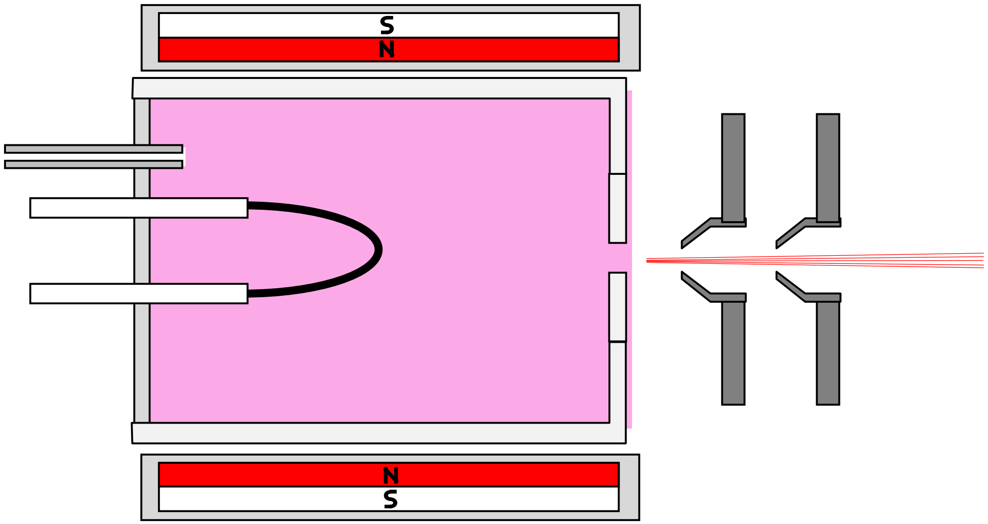
> 50 kV needs
feedthroughs
or bushings

Big Bushings



High Voltage System Design Philosophy

High voltage platform or internal chassis isolation?



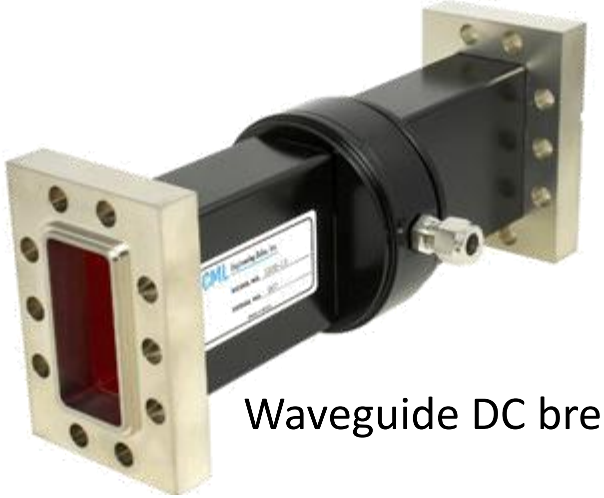
Pros and cons:

Maturity/reliability/space

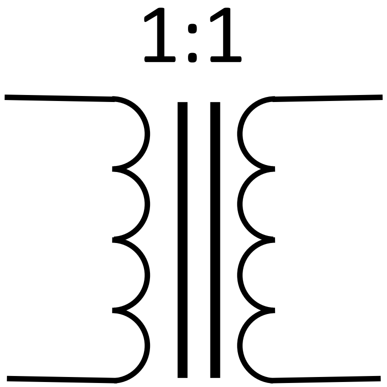
Isolated Power

- How to get power to equipment floating on the HV platform?

Motor- alternator set



Waveguide DC break

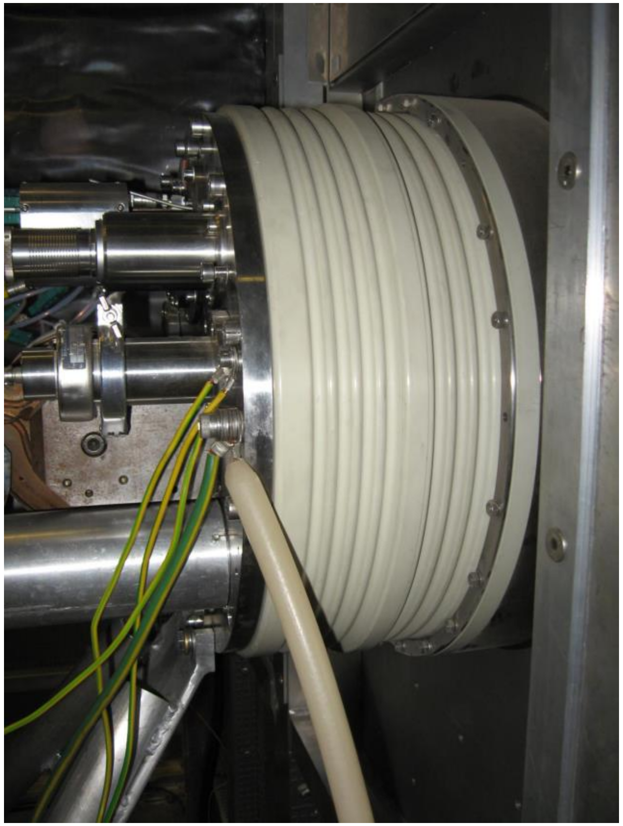


Isolation transformer

Earthing

An earthing system should grow like a tree

Solid single point earth



High voltage platform becomes "Local earth"

Power Supply Technologies

- Transformers
- Semiconductors: Diodes, Transistors, Thyristors, IGBT
- Linear or switched mode
- Cascade rectifier (Greinacher/Cockcroft–Walton multiplier)
- Electron and gas discharge devices:
    - Tetrode, thyratron etc. for switching
    - Klystrons, magnetrons etc. for RF
- Pulse Forming Networks PFN
- Vandergraph, Peloton

High Voltage Power Supply Manufacturers

GLASSMAN HIGH VOLTAGE INC.

SIEMENS

DANFYSIK
A subsidiary of Danish Technological Institute

Heinzinger®
power supplies
supplies your world

ETPS Limited

ULTRAVOLT
Making High Voltage Easier!®

Genvolt
high voltage power supplies

DIVERSIFIED TECHNOLOGIES, INC.®

fug

HiTek Power

ppm POWER

BRUKER

Jema

AHV
AMERICAN HIGH VOLTAGE

EMCO
HIGH VOLTAGE CORPORATION

Matsusada Precision

AN ISO 9001 COMPANY
KEPCO®
THE POWER SUPPLIER™

APPLIED KILOVOLTS

Spellman®
High Voltage Electronics Corporation

GAMMA

TDK

TDK-Lambda

a.l.e. systems

Custom Built Power Supplies

- Tight specification is essential if engaging a manufacturer
- Or of course you could make your own if you have the experience…

Safety

- Electric Shocks can kill
- Stored energy in capacitors

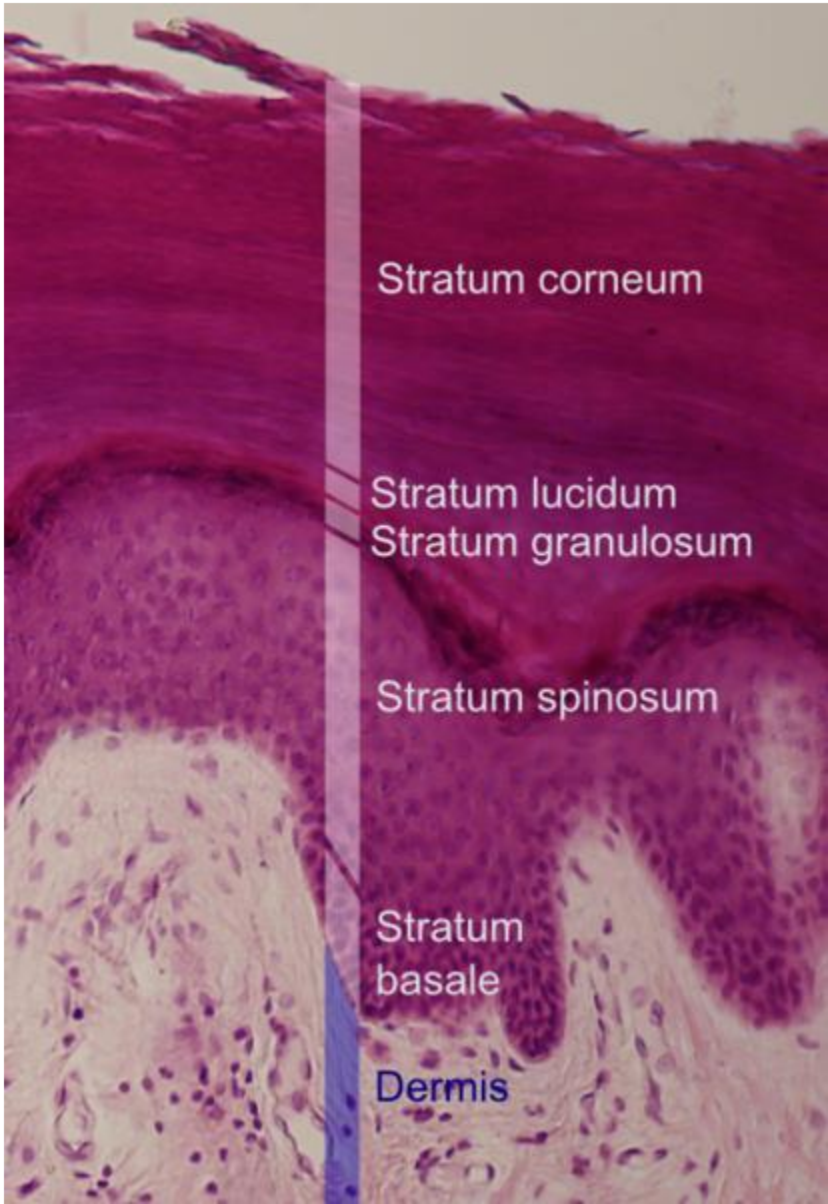
  $\frac{1}{2}CV^2$ = 0.5 x 1 μF x 30 kV = 450 J

- X-rays

Electric Shocks

Hand to hand resistance:
100 kΩ dry/thick skin
1 kΩ wet/broken skin

- The stratum corneum breaks down 450–600 V leaving 500 Ω
- You can feel 5 mA
- 60 mA can fibrillate the heart



HV Safety Philosophy

1. Impossible to accidently lock someone in the HV area.
2. Ability to shut down the power inside and outside the HV area.
3. Impossible to power on the HV without locking the area.
4. Impossible to enter the HV area without making it safe.

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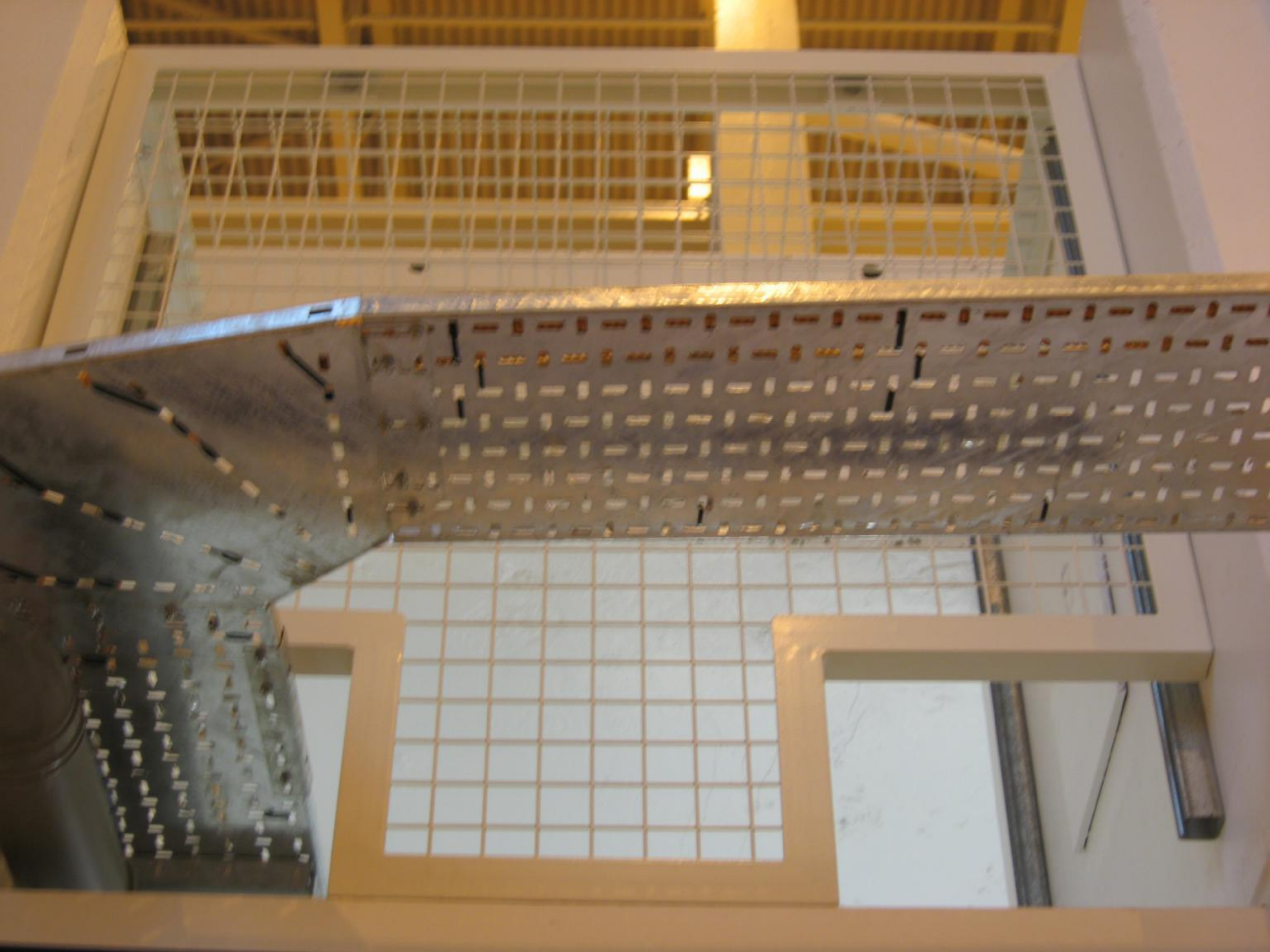
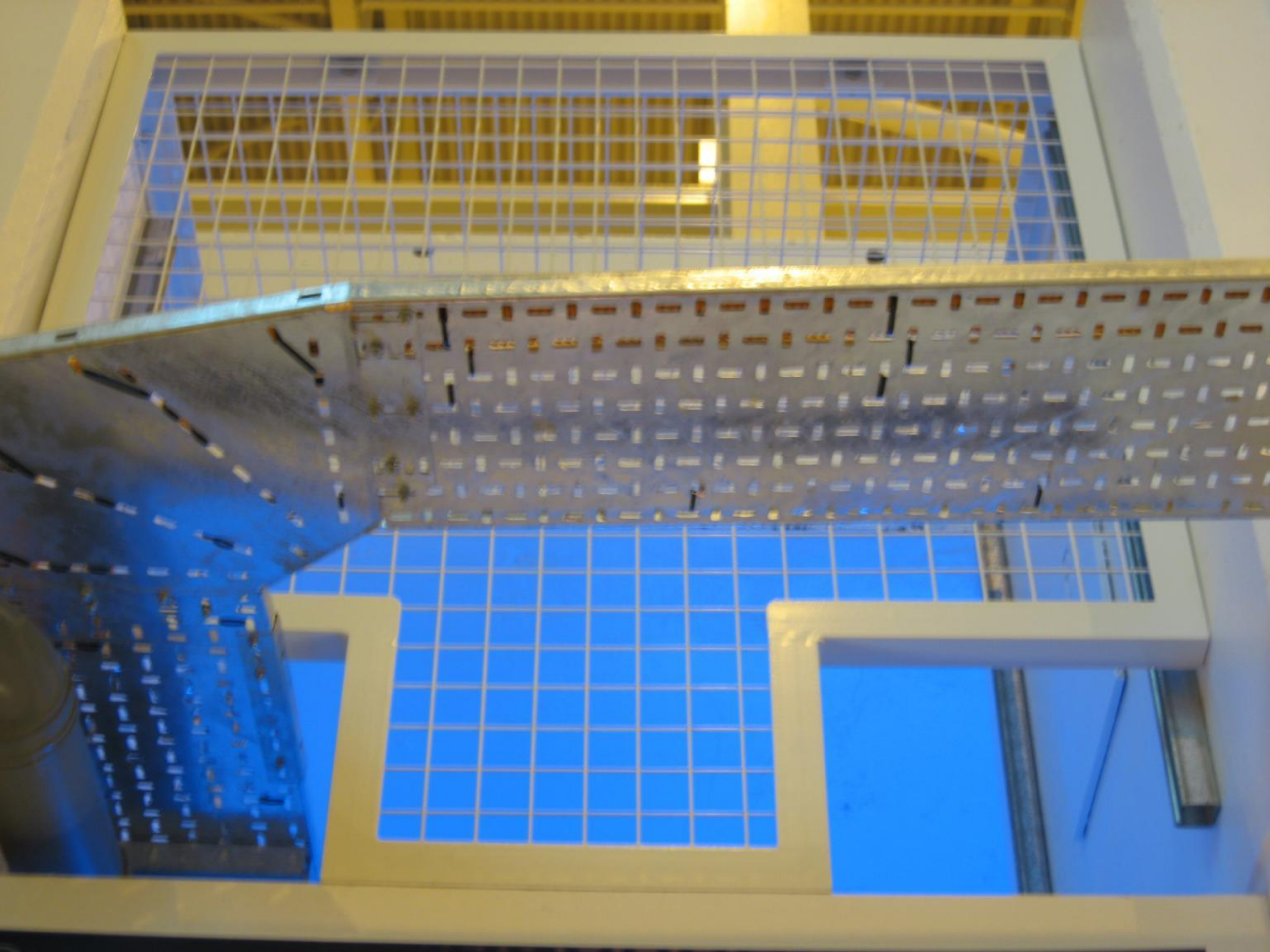
SEARCH






SMASH GLASS TO OPEN
Emergency
Exit
Break Glass Tube & Push Here

HV Safety Philosophy

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EMERGENCY
CALL POINT
BREAK GLASS
PRESS HERE
DANGER
230V
LIVE TERMINALS
INSIDE
HV OFF

HV Safety Philosophy

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CS


CS


BIAS03


SONIAC VAULT
2314210

HV Safety Philosophy

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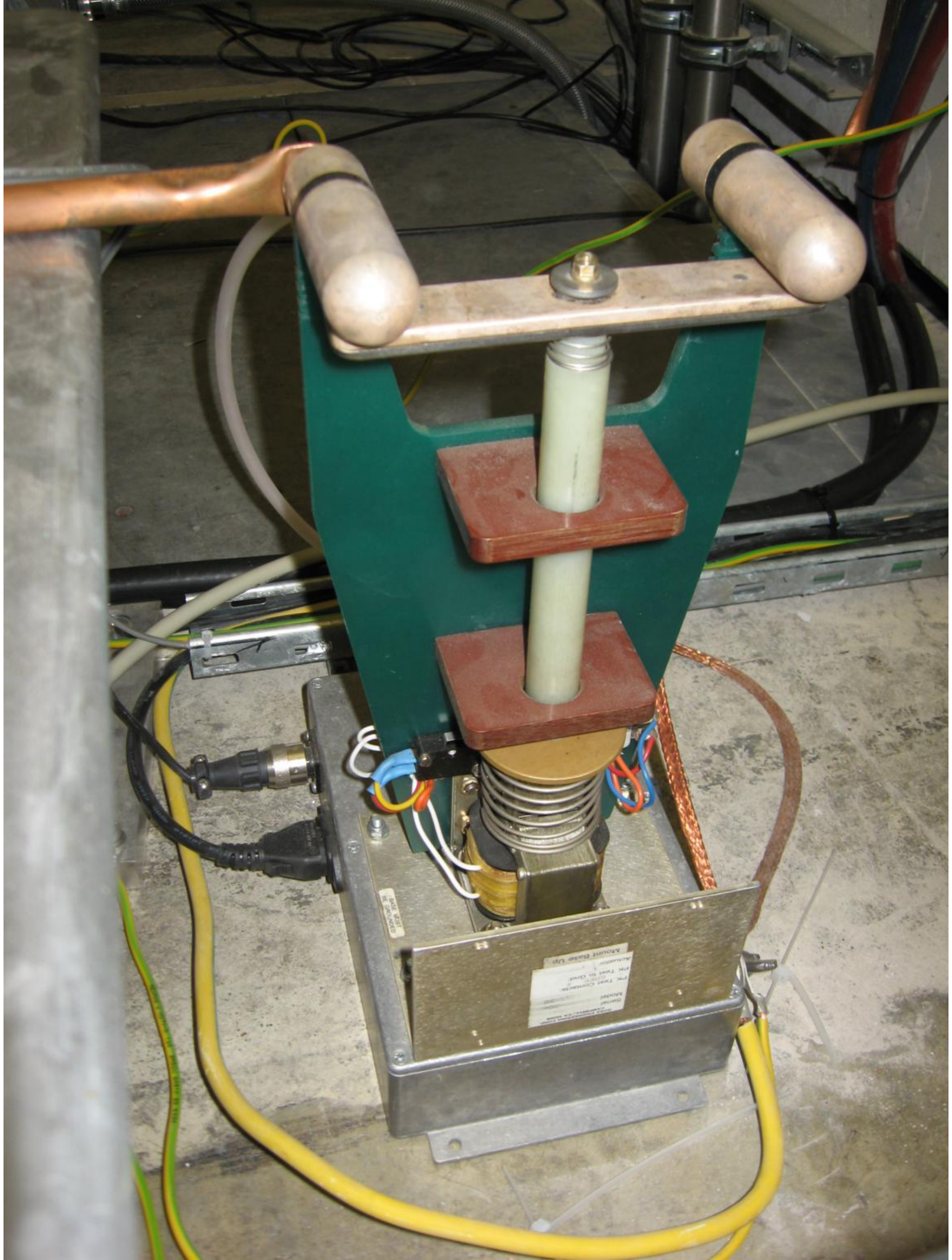
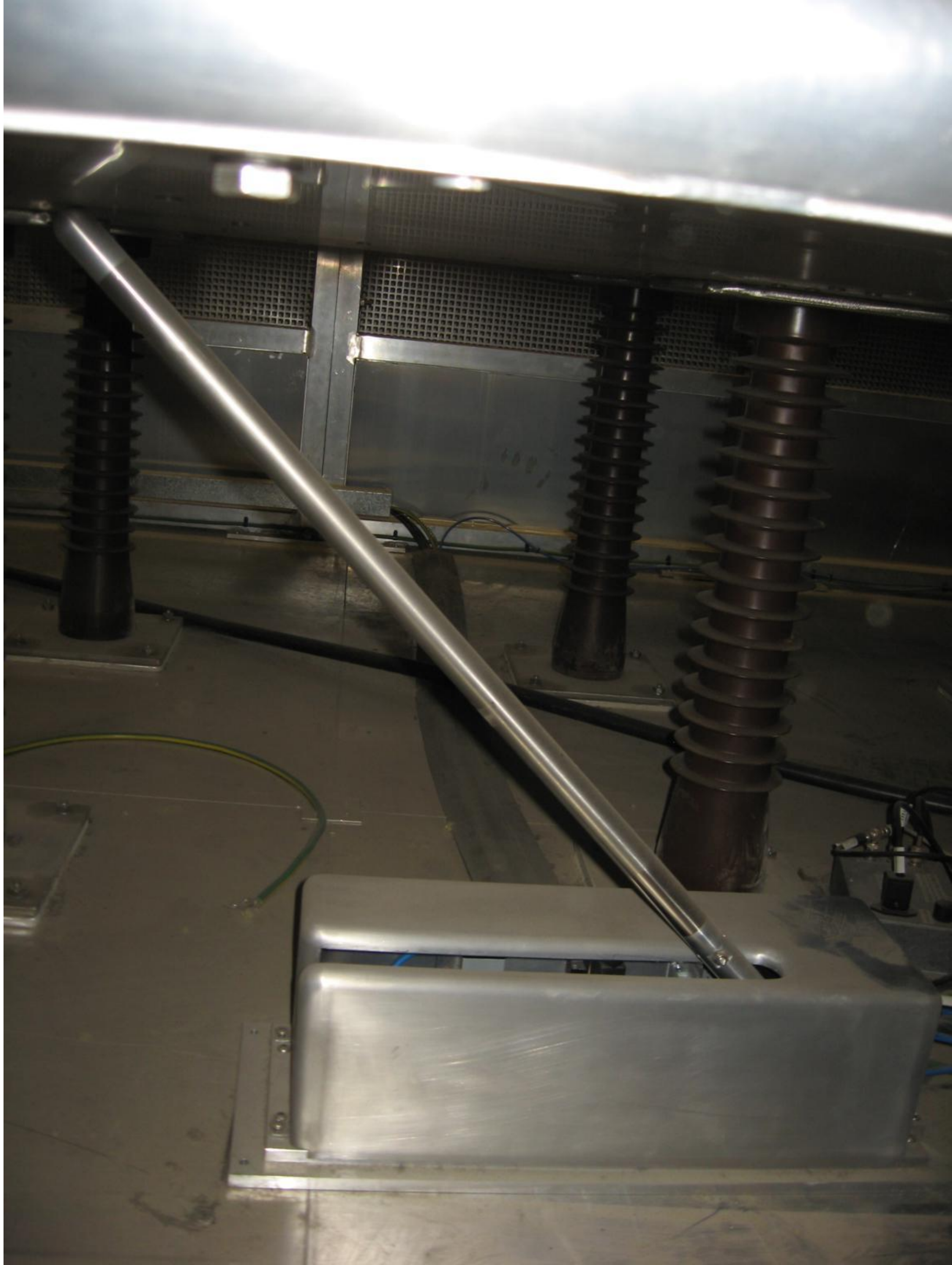
CSI

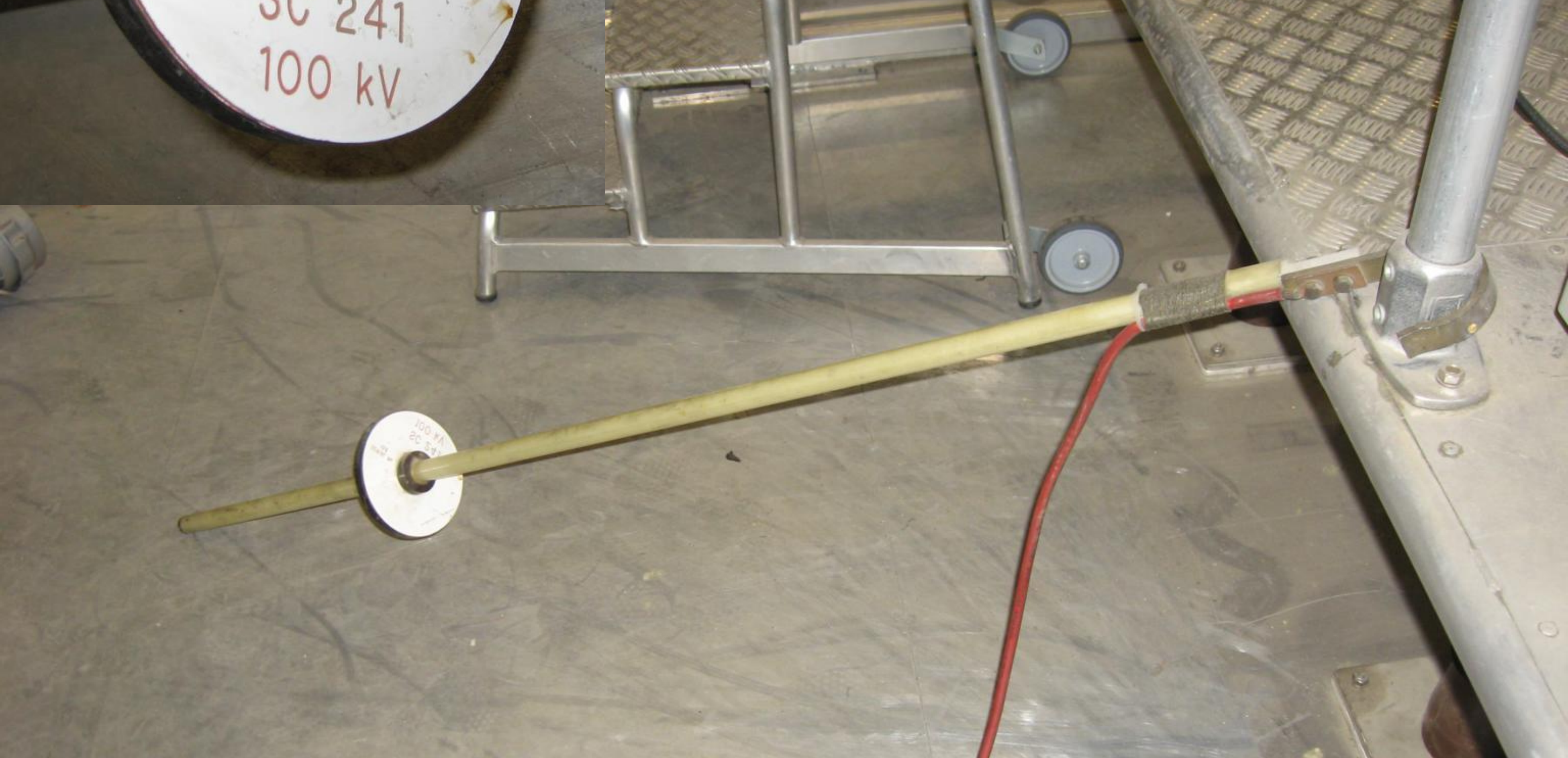
Automatic Earthing System



Automatic Earthing System



Earth Stick



Earth stick should be hung just inside the entrance of the high voltage area

You can never prevent humans from circumventing safety systems...

But you must make sure that they require some effort to wilfully bypass

Complacency and familiarity can kill

Thank you for listening

Example of very bad safety systems:

Cautionary tale of Dr. Jon Osterman...


INTRINSIC FIELD
LABORATORY

Let that be a lesson!