Technological Aspects: High Voltage

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Talk Outline

- High voltage and ion sources
- Electric field calculation
- Electrical breakdown
- Insulators
- Partial breakdown
- Statistical variability
- Factors affecting breakdown voltage
- Cables and terminations
- Ancillary equipment
- Earthing and safety

Uses of High Voltages in Ion Sources

- 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 (e.g. Hydrogen)

High temperatures

Other contaminants (e.g. Cs)

Magnetic fields

Large amounts of charge carriers

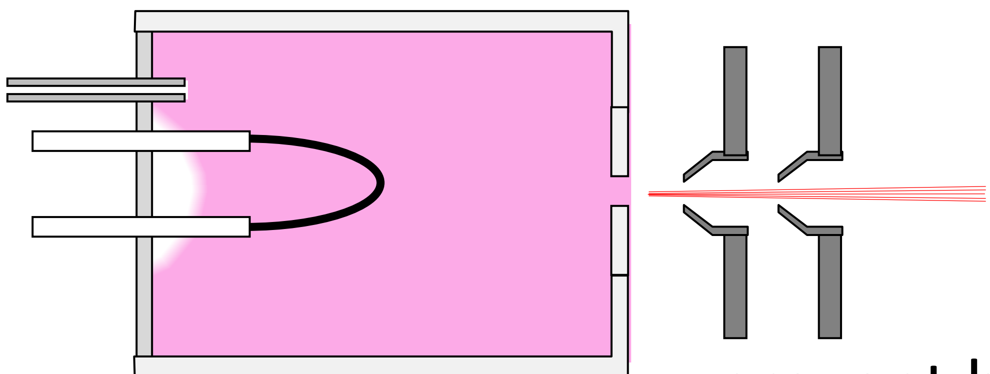
Stray beams: electrons and ions

Compact design

Main Aim of High Voltage Design for Ion Sources

Produce reliable breakdown

... where we want it



prevent breakdown

...where we don't want it

The two regions are only mm apart!

High Voltage Breakdown

- Electric field strength is the primary factor
- In general high voltage 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:

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

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

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

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

or

Poisson's Equation

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

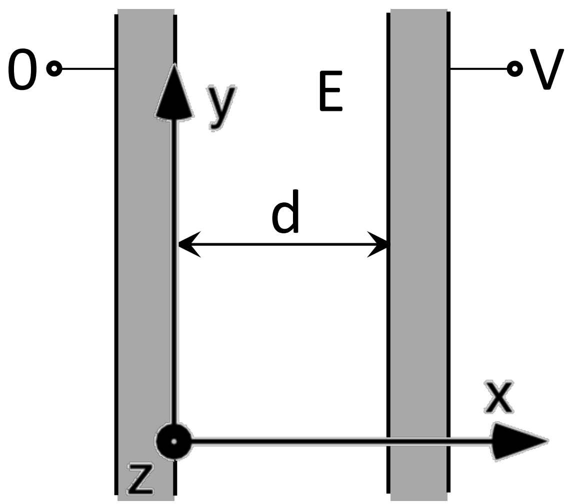
if ρ = 0:

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

Infinite parallel plates:



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

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

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

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

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

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

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

$$\Rightarrow \phi(x) = c_1 x + c_2$$

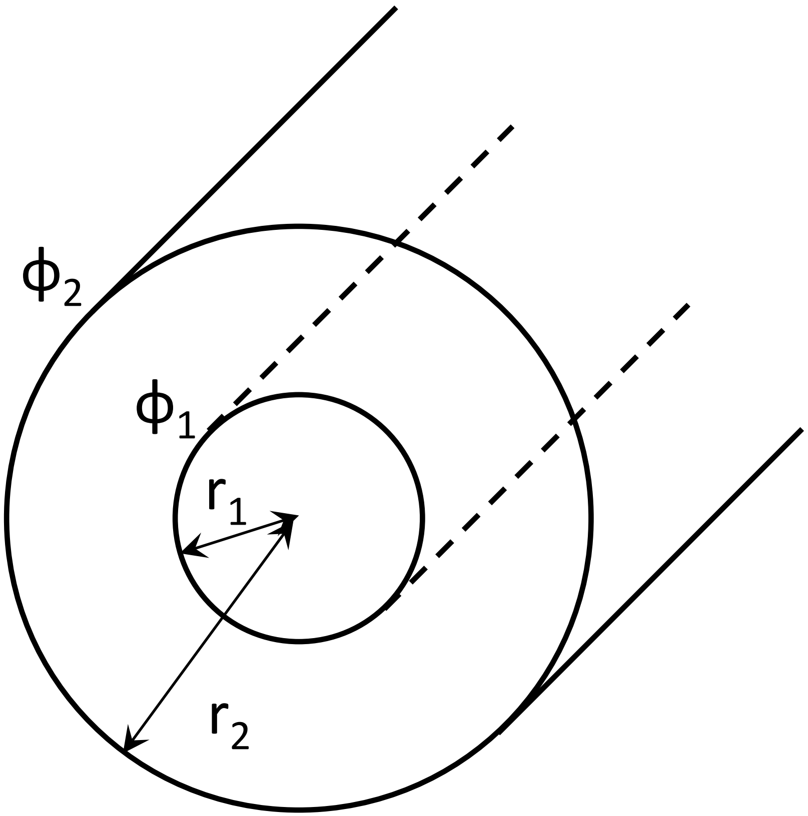
At $x = 0$, $\phi = 0$ and at $x = d$, $\phi = V$

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

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

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...

Finding Electric Field Distributions

Teledeltos paper

Silver Paint

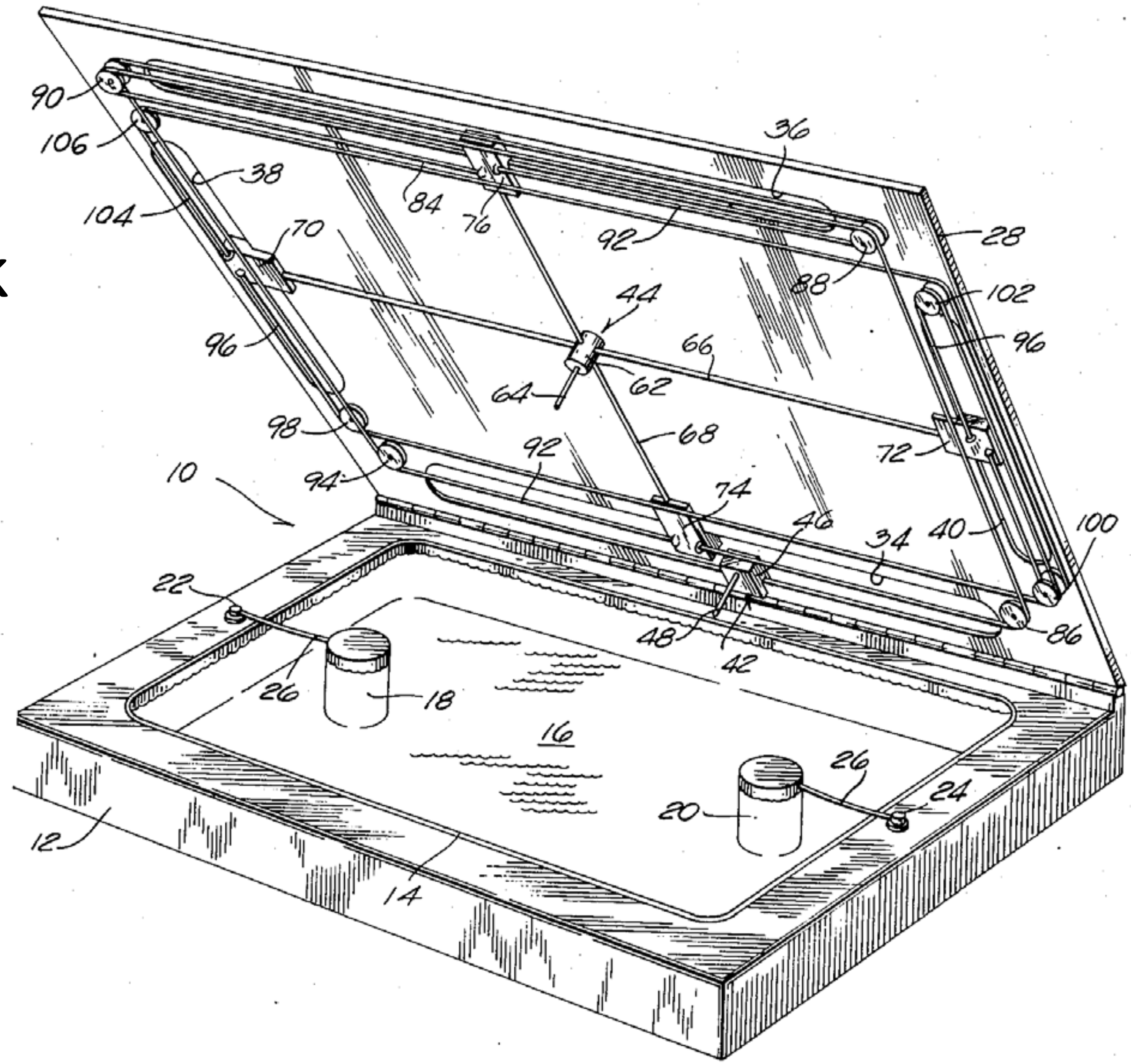
Power supply,
voltmeter and probe

Manually find
equipotentials

Finding Electric Field Distributions

Automated

Electrolytic tank

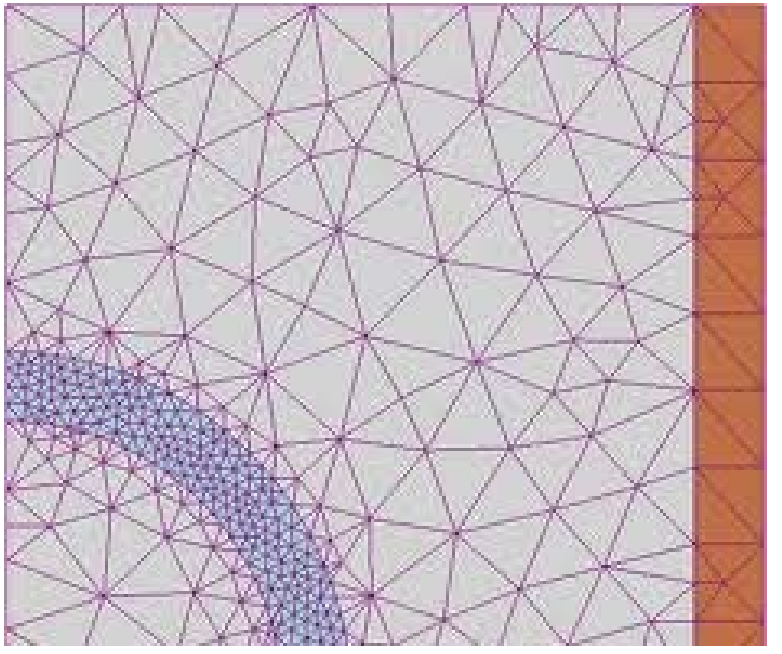


Thankfully we have Computers

Numerically Solving Poisson's Equation

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

Apply discrete form to finite elements



Direct methods

- Gaussian elimination
- LU decomposition method

Iterative methods

- Mesh relaxation methods
    - Jacobi
    - Gauss-Seidel
    - Successive over-relaxation method (SOR)
    - Alternating directions implicit (ADI) method
- Matrix methods
    - Thomas tridiagonal form
    - Sparse matrix methods: Stone's Strongly Implicit Procedure (SIP); Incomplete Lower-Upper (ILU) decomposition
    - Conjugate Gradient (CG) methods: Incomplete Choleski Conjugate Gradient (ICCG); Bi-CGSTAB
    - Multi–Grid (MG) method

Take your pick!

… but you won't be the first

There are many solvers available to download
Standard Masters degree project
Written in every language, run on every platform

Mostly 2D
Poor geometry input
Poor meshing
Poor post processing
No/poor support

If you want a free 2D solver:

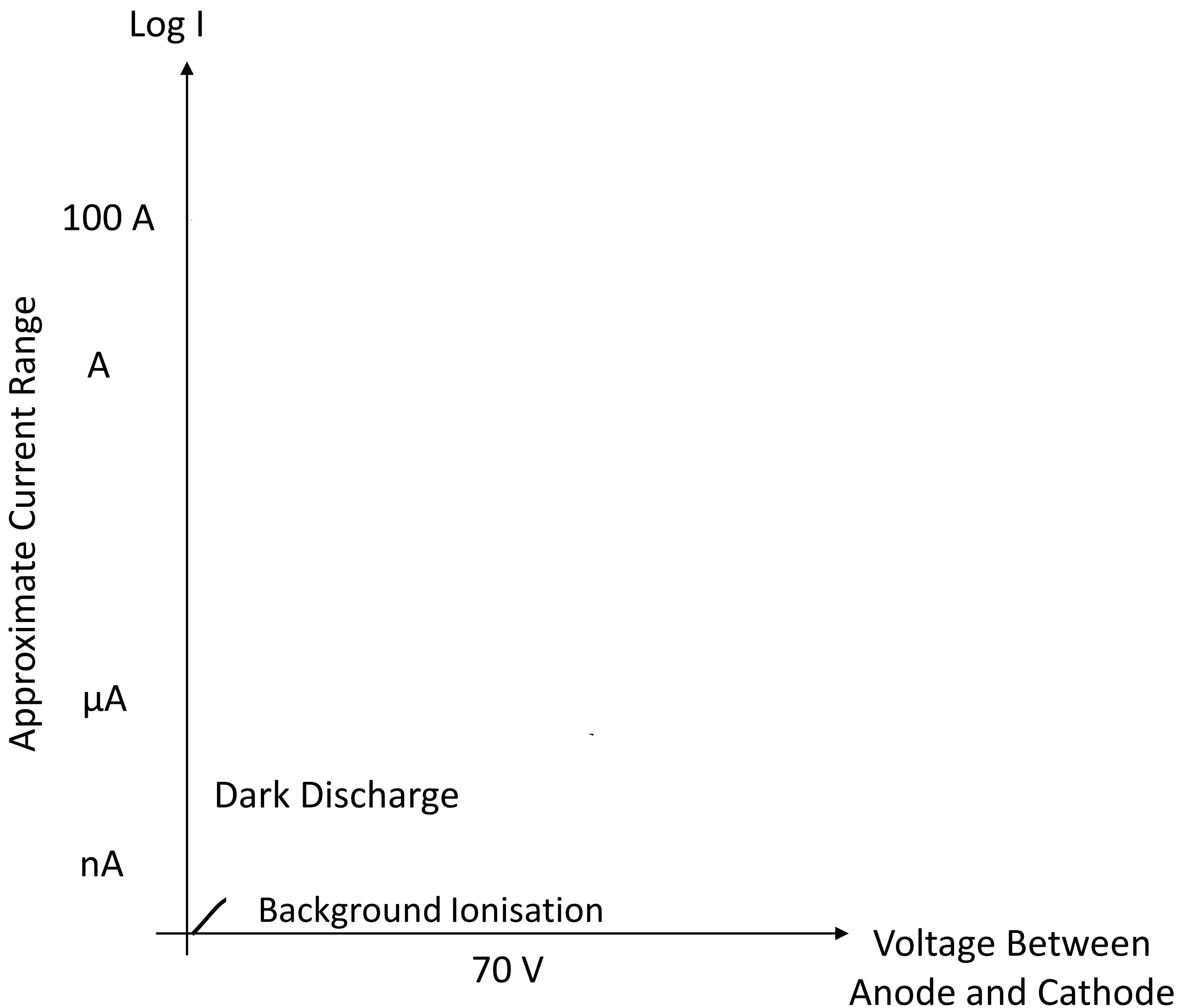
LAACG

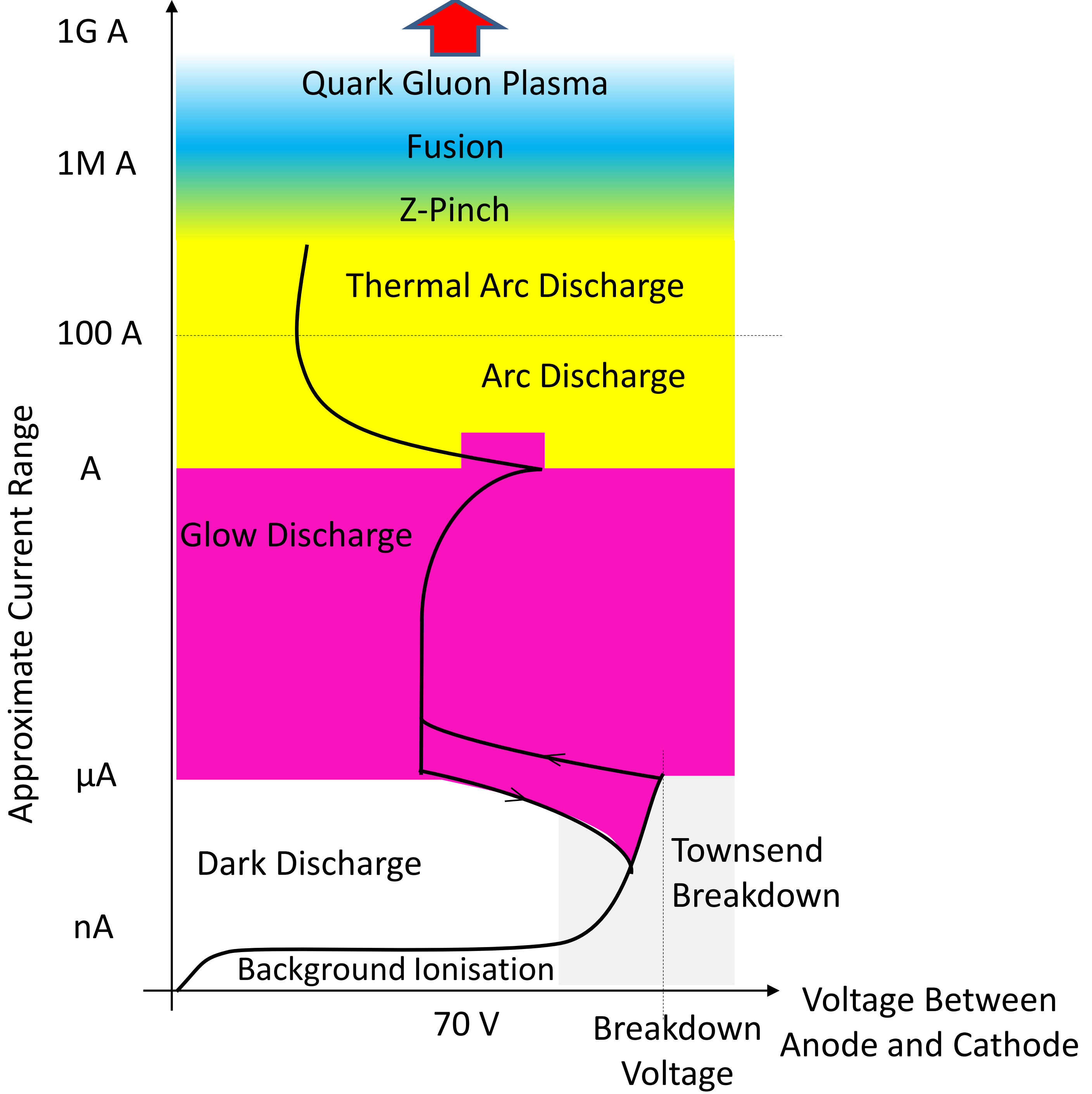
Poisson Superfish

Commercial 3D Modelling Software

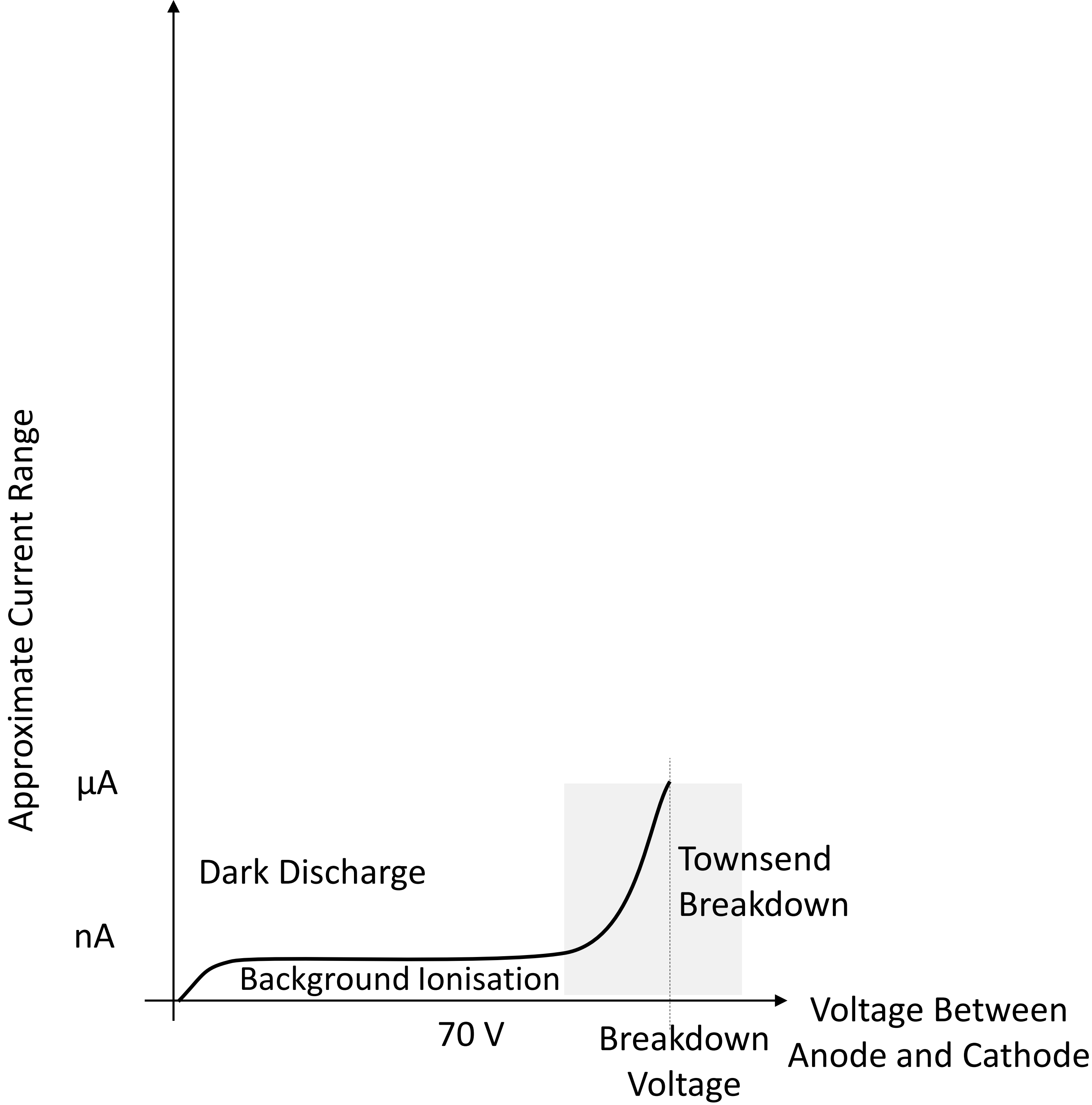
Plus others…

Electrical Discharges





1G A
1M A
100 A
A
µA
nA
Approximate Current Range
Quark Gluon Plasma
Fusion
Z-Pinch
Thermal Arc Discharge
Arc Discharge
Glow Discharge
Dark Discharge
Townsend Breakdown
Background Ionisation
70 V
Breakdown Voltage
Voltage Between Anode and Cathode



Approximate Current Range
μA
nA
Dark Discharge
Background Ionisation
Townsend Breakdown
70 V
Breakdown Voltage
Voltage Between Anode and Cathode

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

- Global break down can only occur when a highly conductive channel is formed between the two electrodes
- The journey towards high voltage breakdown depends on the degree of non uniformarity of the electric field
- Geometry of electrodes and materials and environment all play a critical role

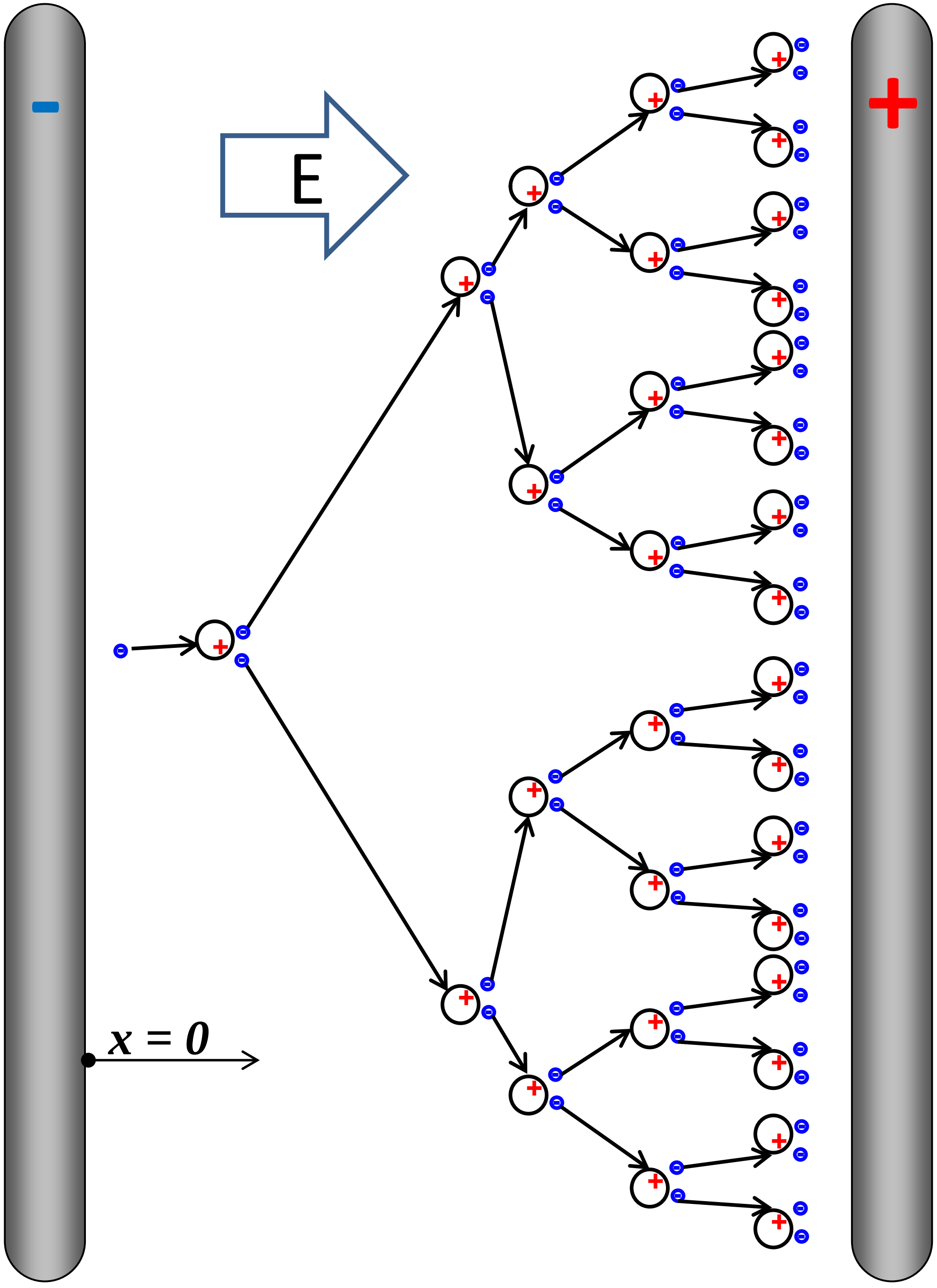
Avalanche

John Townsend
"Townsend discharge"
1897

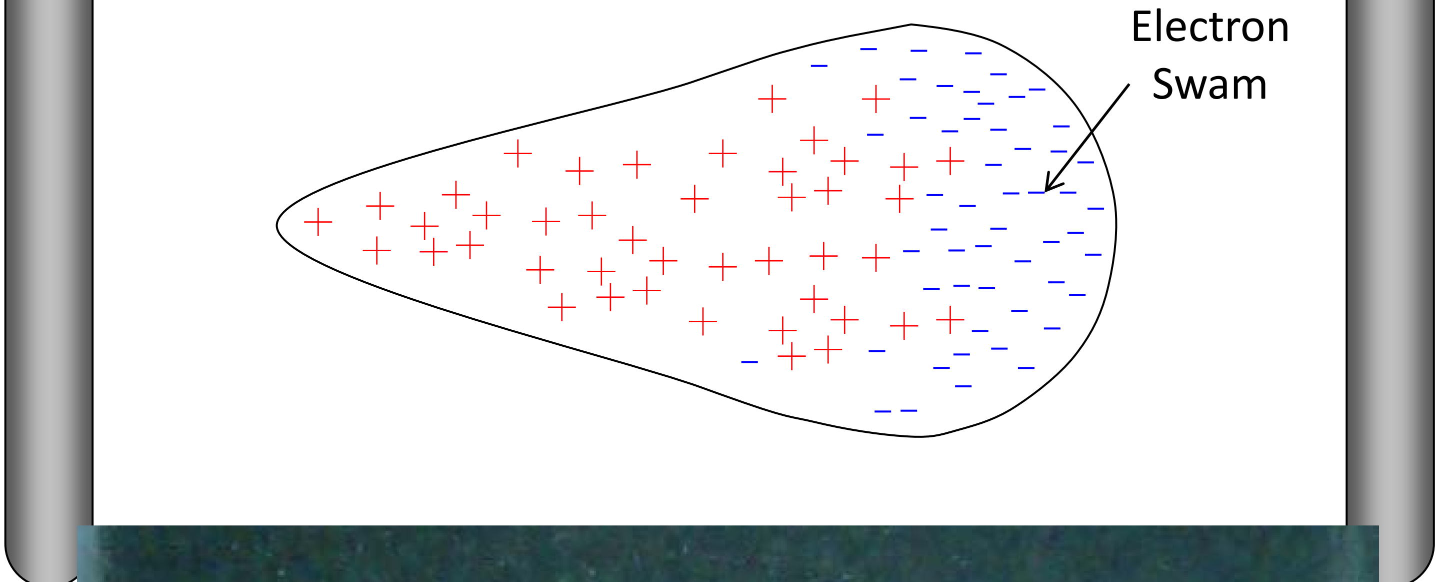
$$dn_x = n_x \alpha dx$$

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

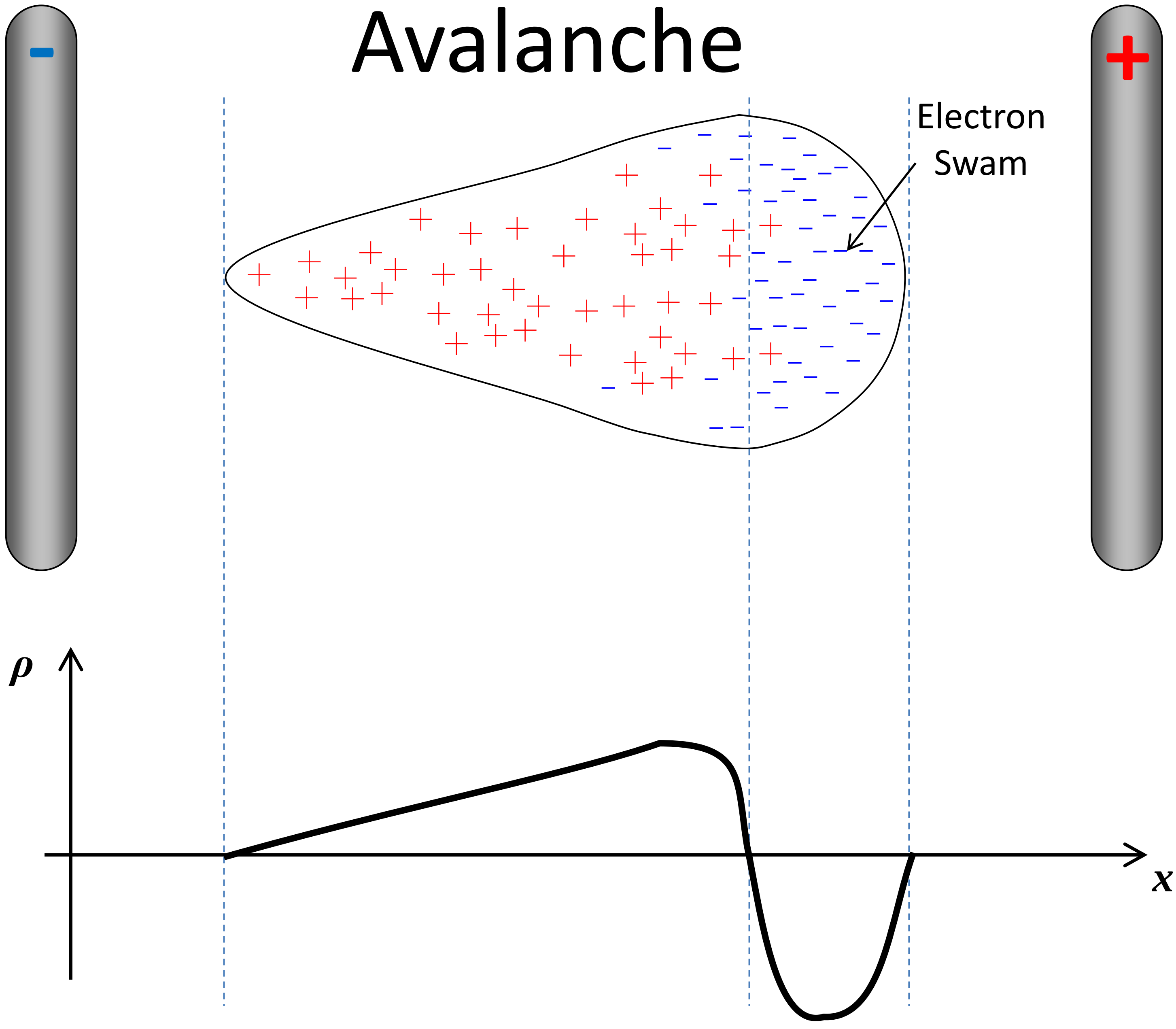
$$n_x = n_0 e^{\alpha x}$$



Avalanche

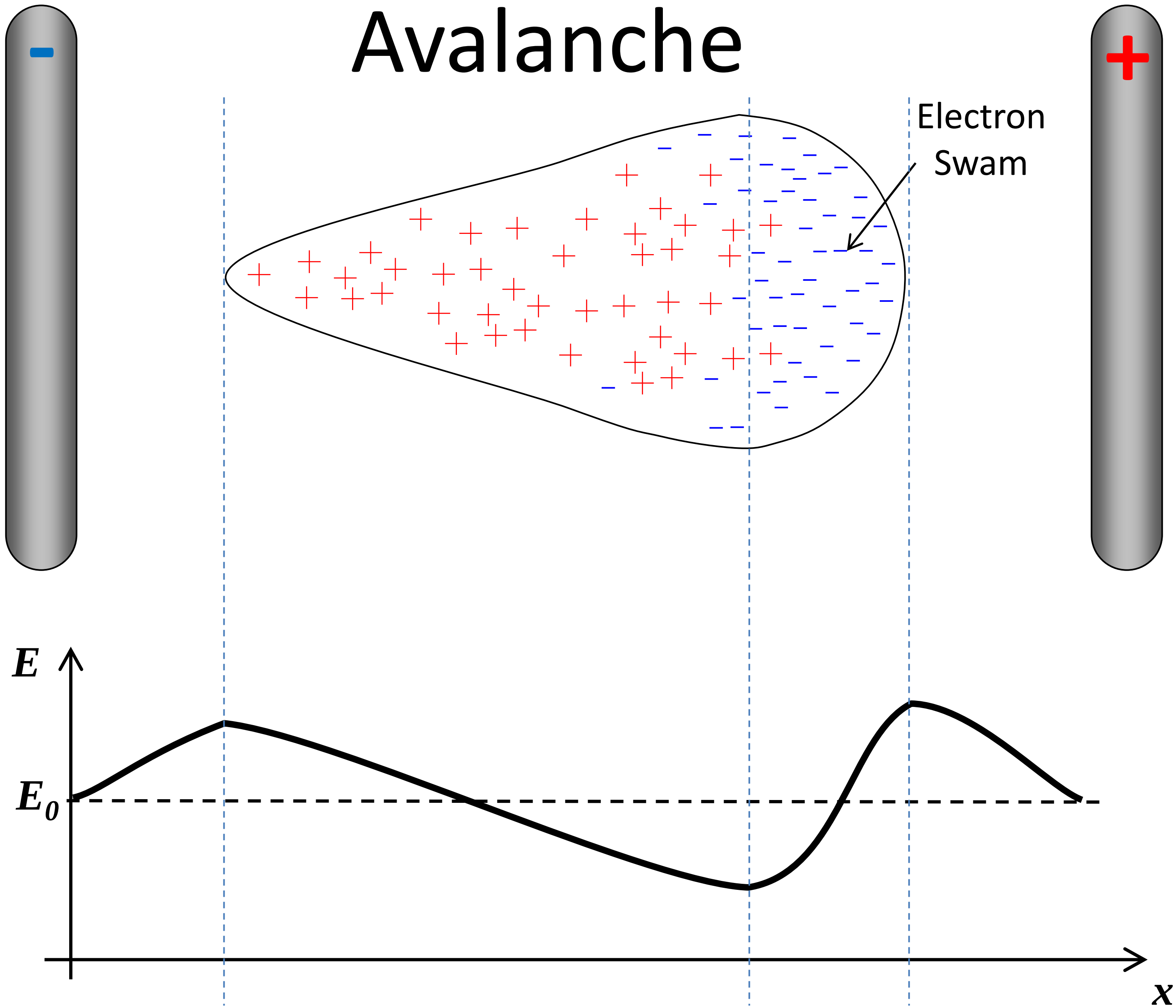


Avalanche

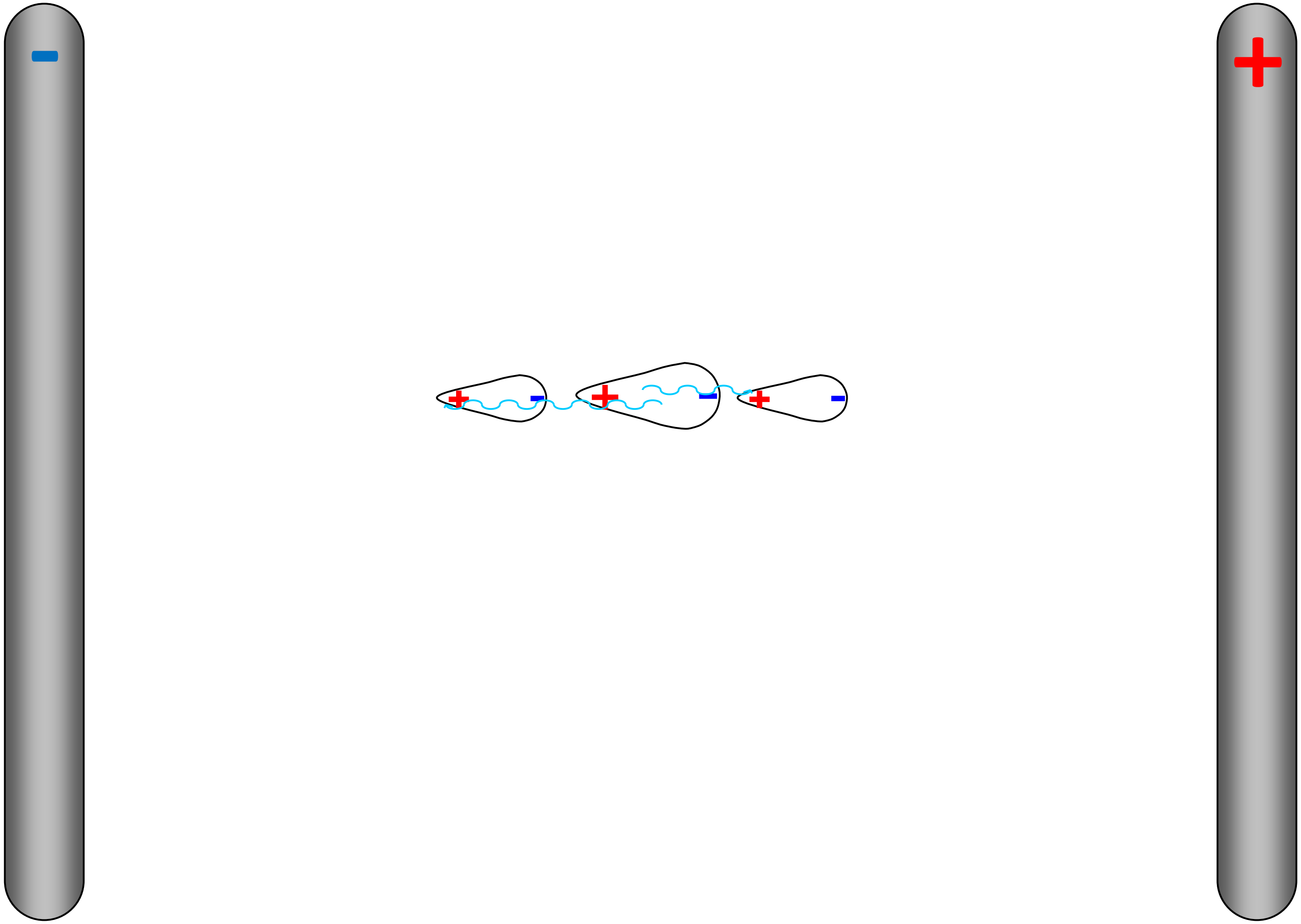


Avalanche

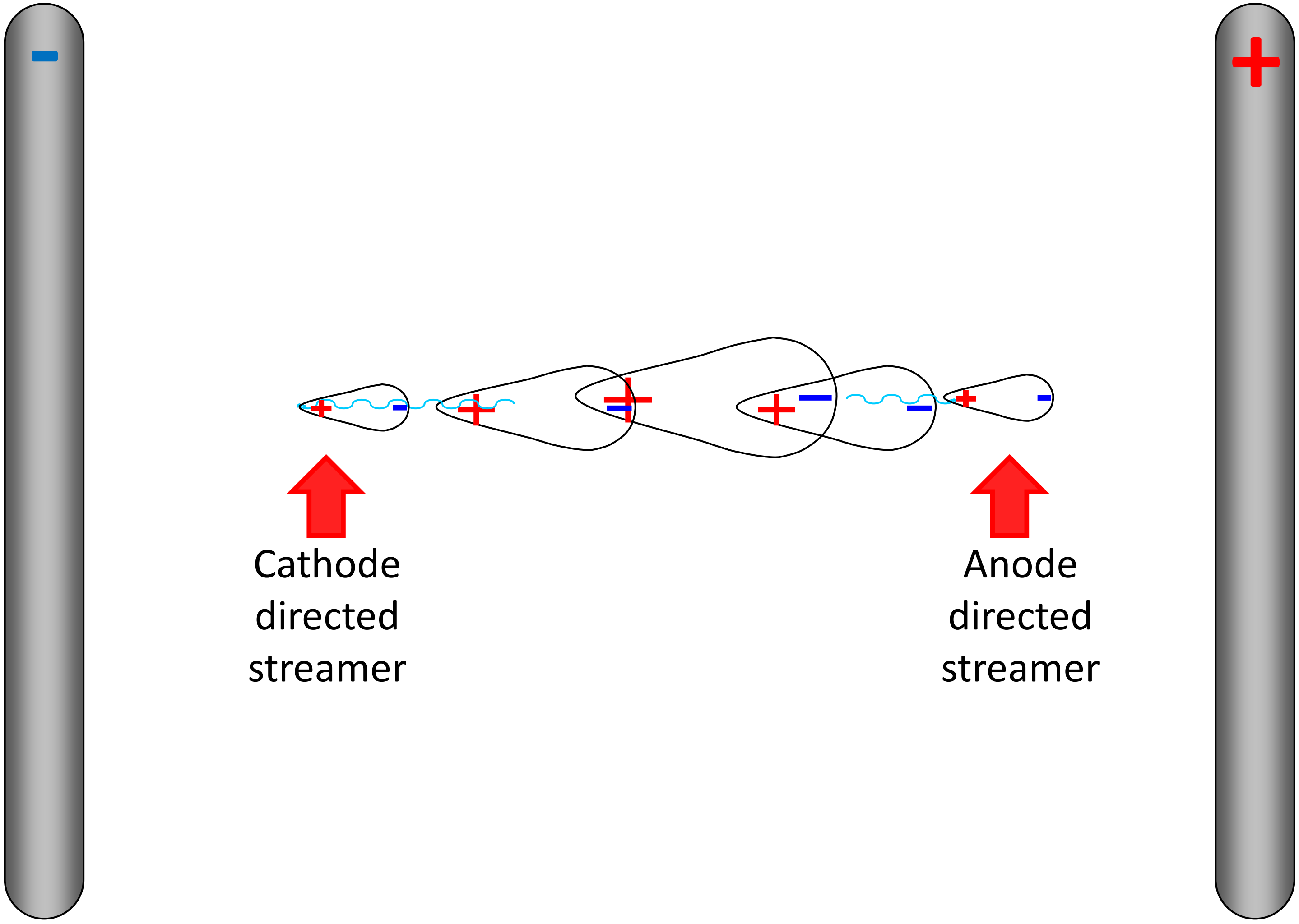
Avalanche



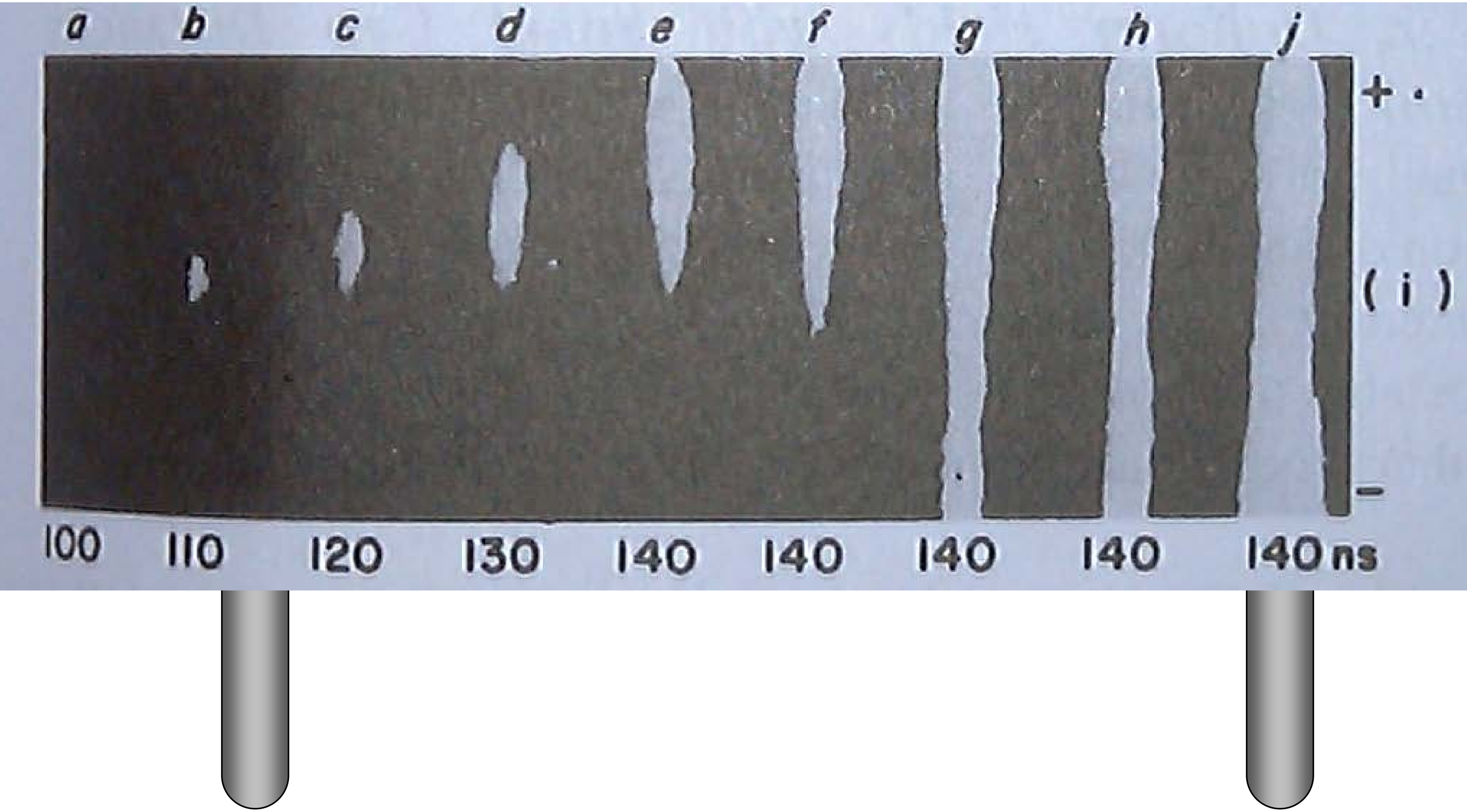
Streamer



Streamer



Streamer



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

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

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

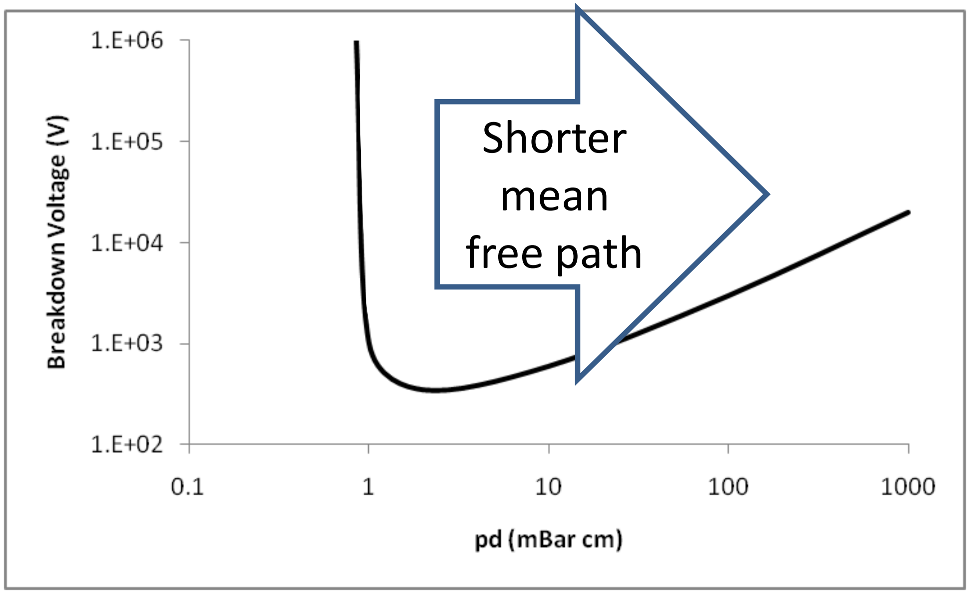
Self sustaining discharge resulting in breakdown when:

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

Townsend Criterion for Breakdown

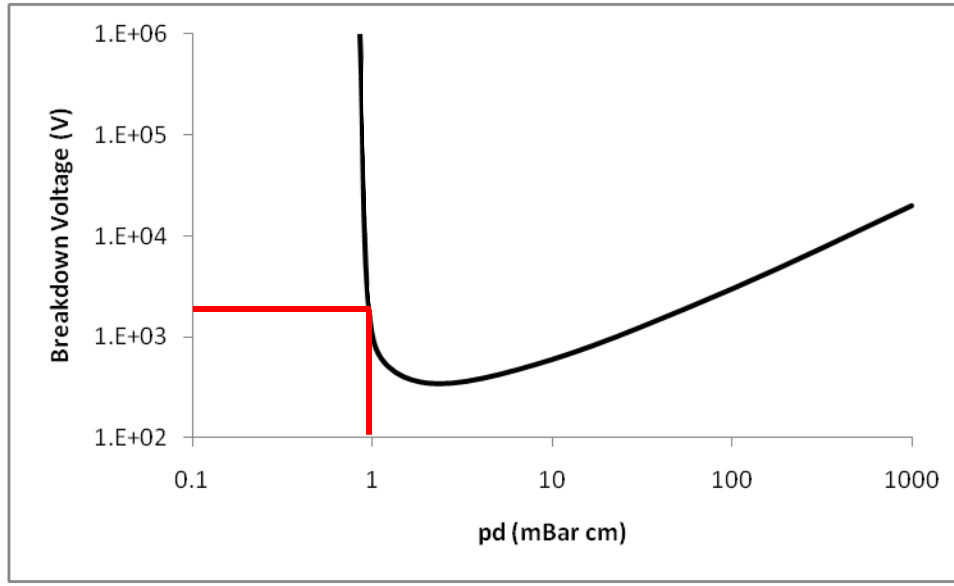
Paschen Curve

Friedrich Paschen 1889



Paschen Curve

Friedrich Paschen 1889

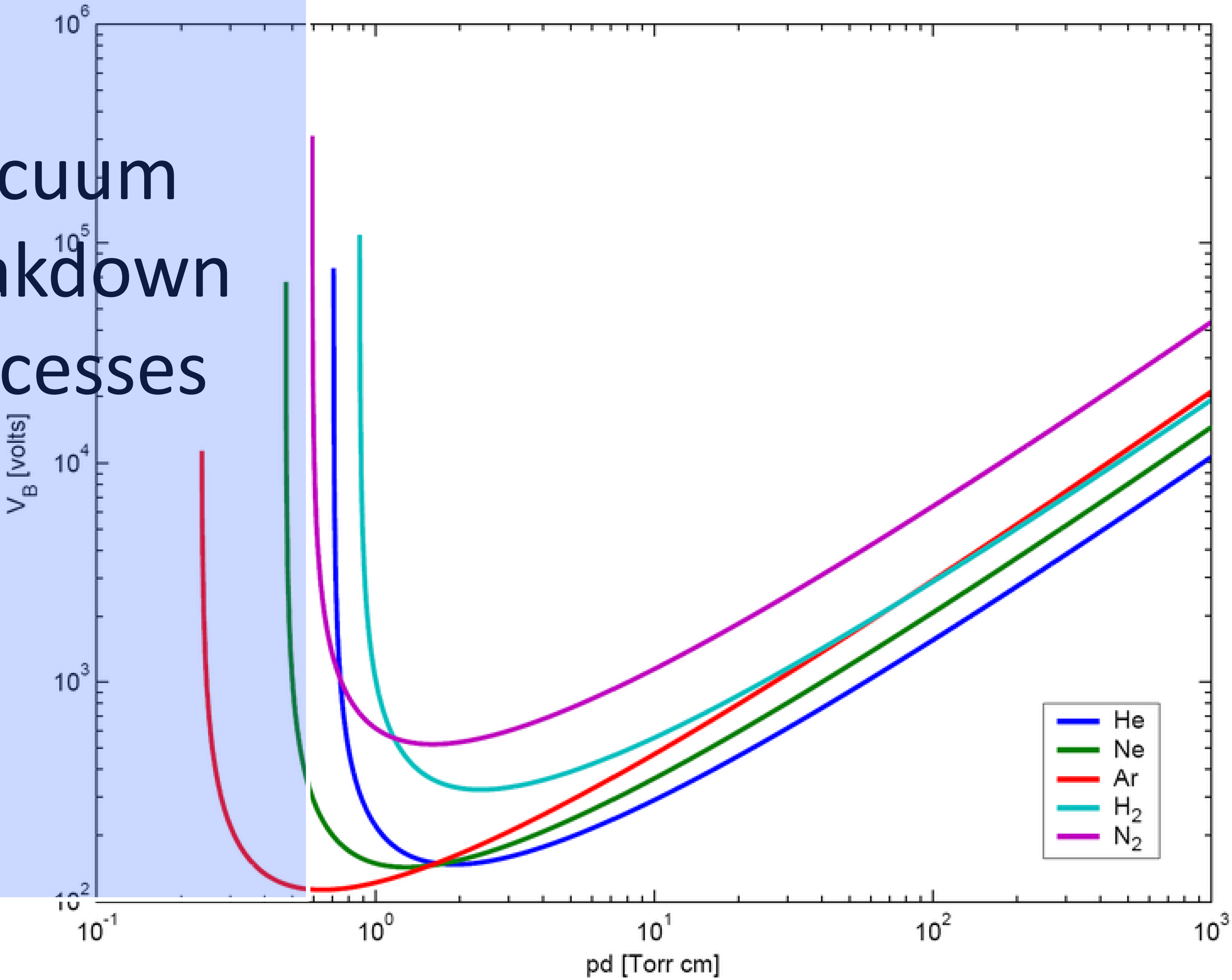


Operating just below the Paschen Minimum:

Longer gaps have

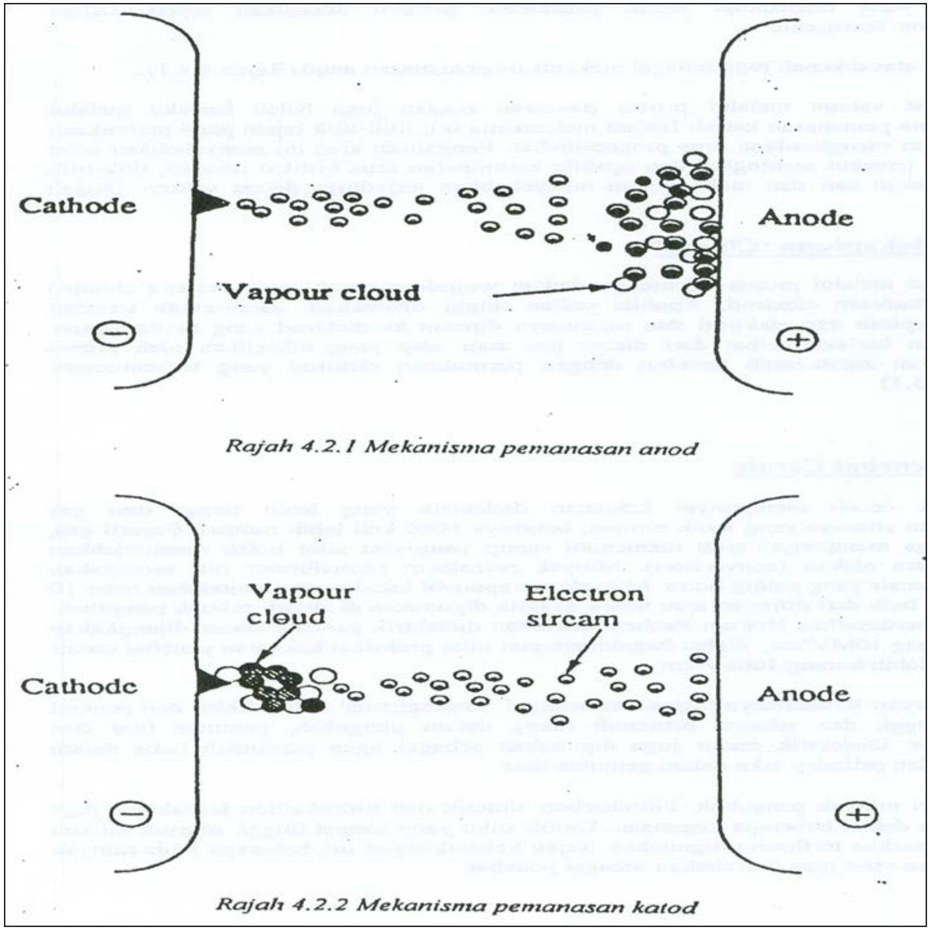
lower breakdown voltages!

Vacuum Breakdown Processes



Vacuum Breakdown

Insulating micro-inclusions can also cause field enhancement



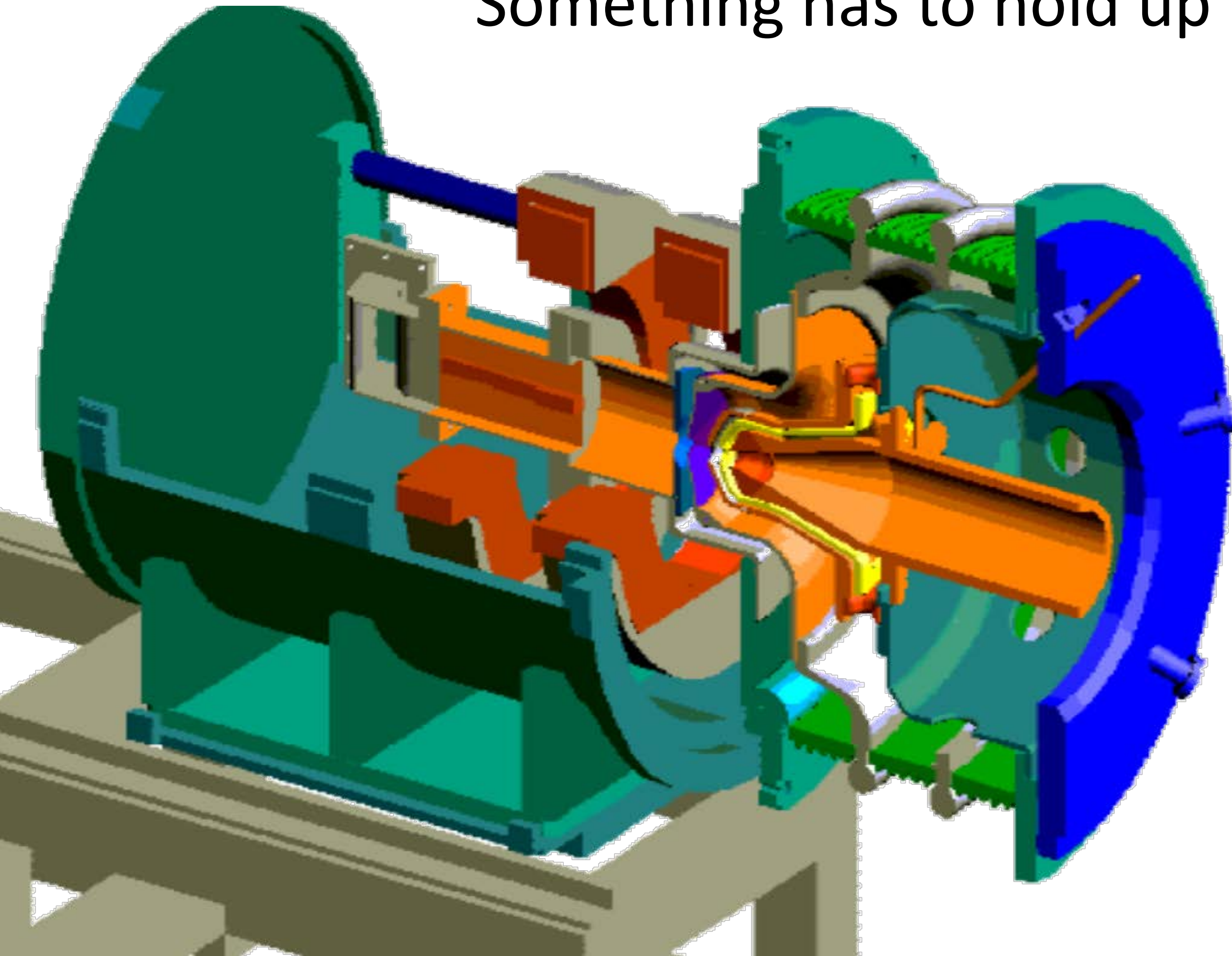
Extraction conditioning

Kilpatrick

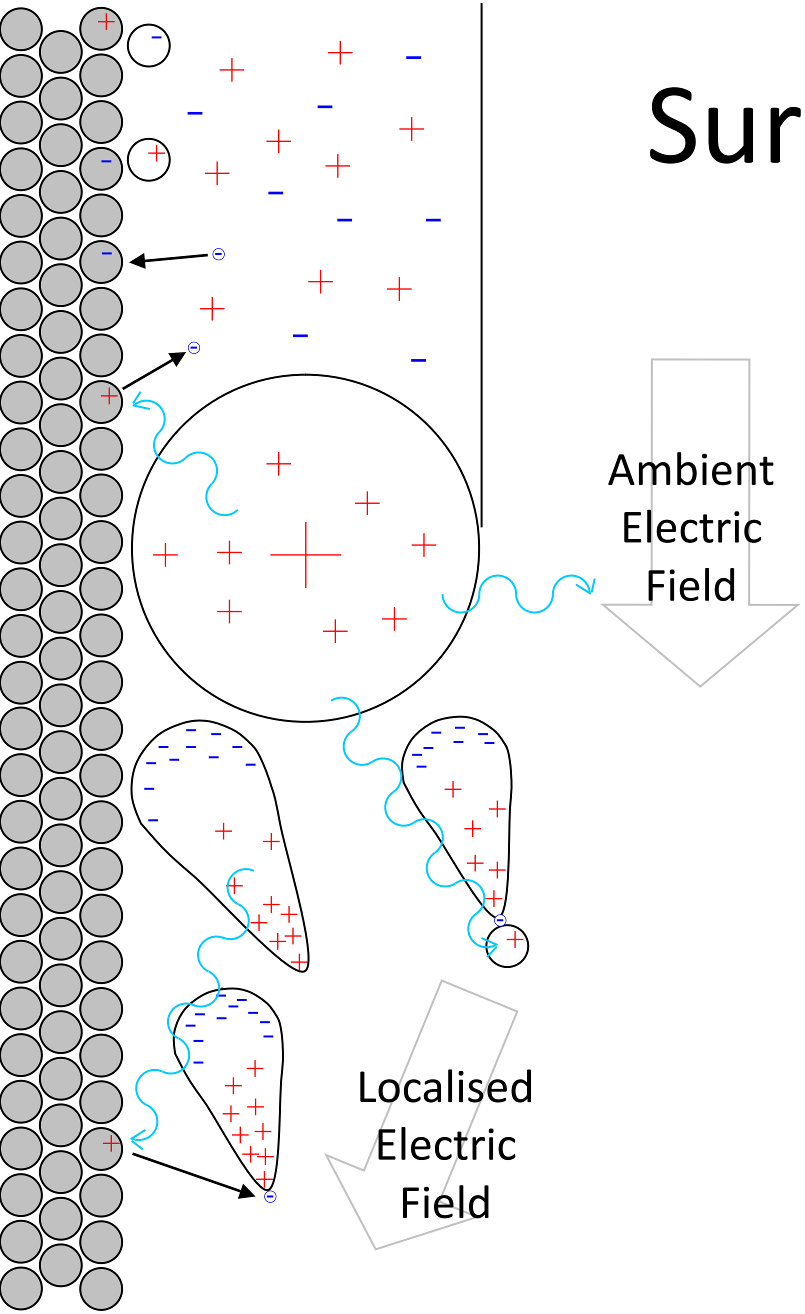
$$f = 1.64\,\mathrm{MHz} \cdot \left(\frac{E}{E_0}\right)^2 \cdot \exp\left(-8.5\,\frac{E_0}{E}\right), \text{with } E_0 = 1\,\frac{\mathrm{MV}}{\mathrm{m}}$$

Insulators

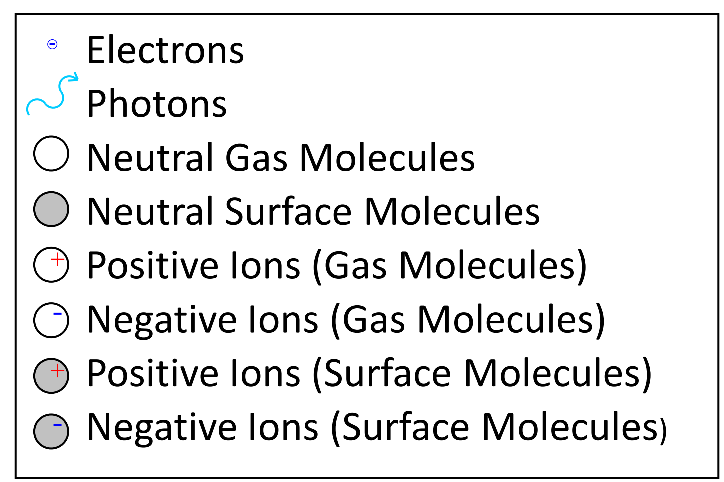
Something has to hold up the electrodes

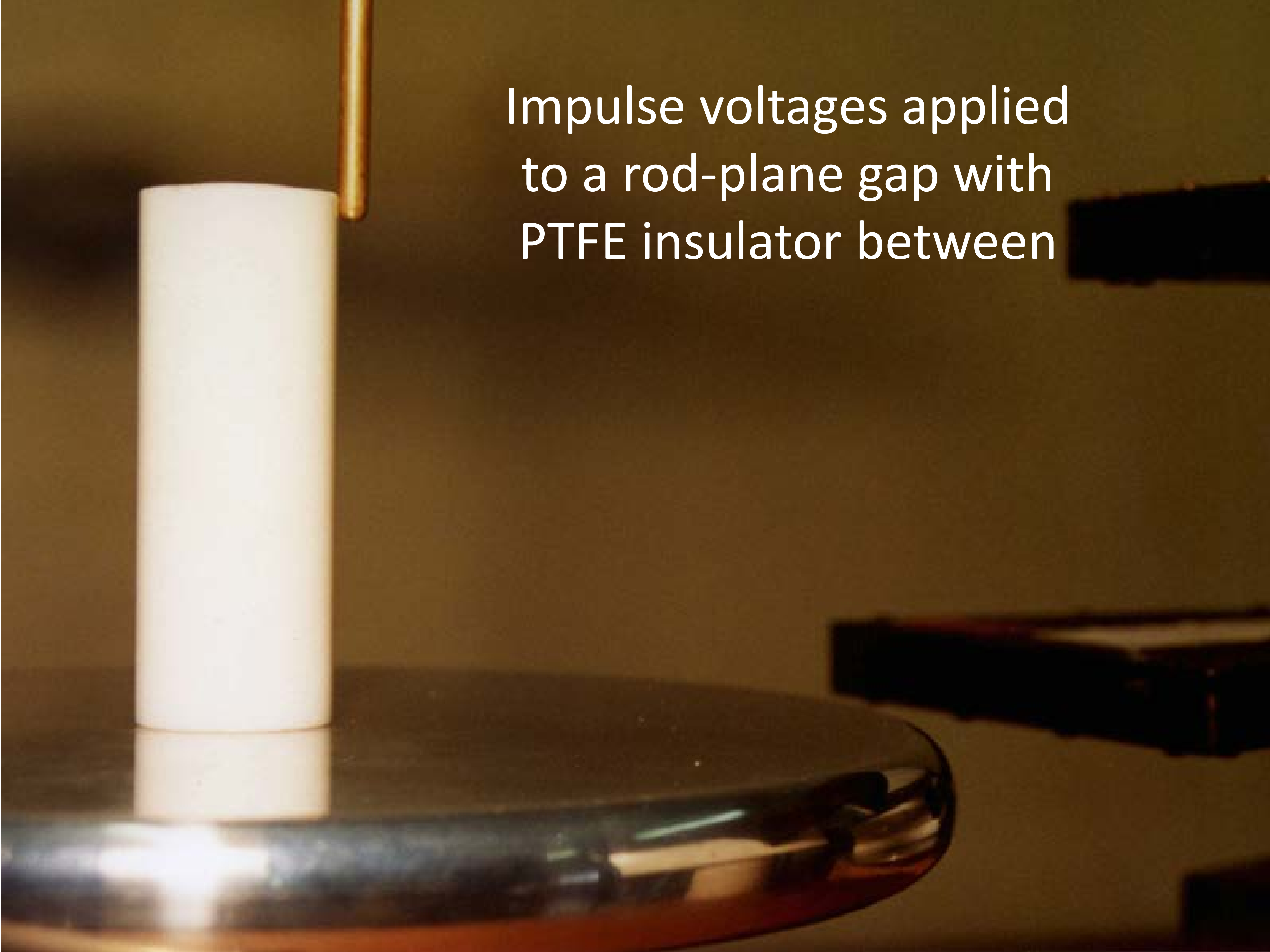


Surface Breakdown

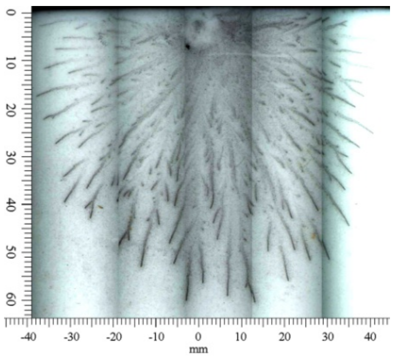


Insulator surfaces are the weakest part of the insulation system

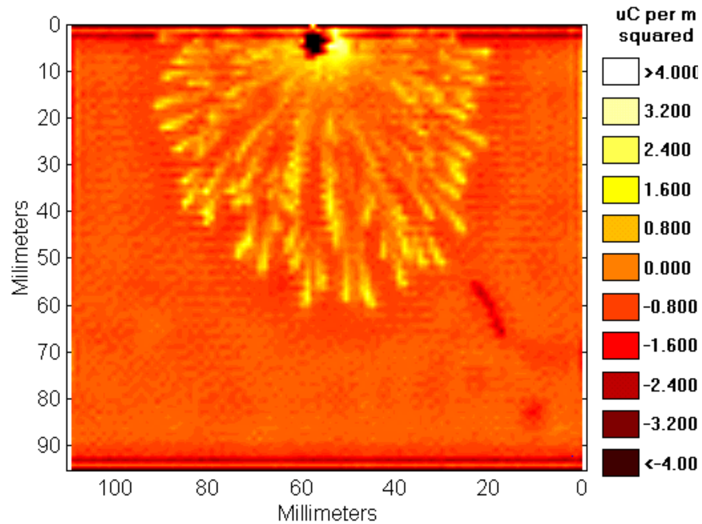



Impulse voltages applied
to a rod-plane gap with
PTFE insulator between

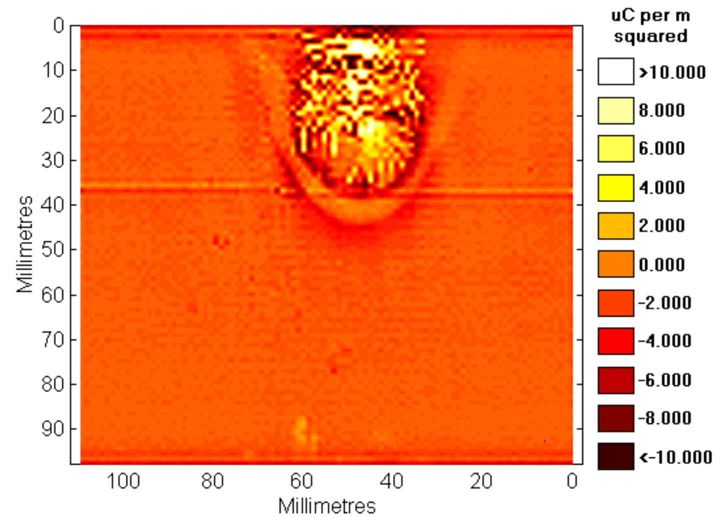
Surface Charging



Dust Figure



Charge Distribution



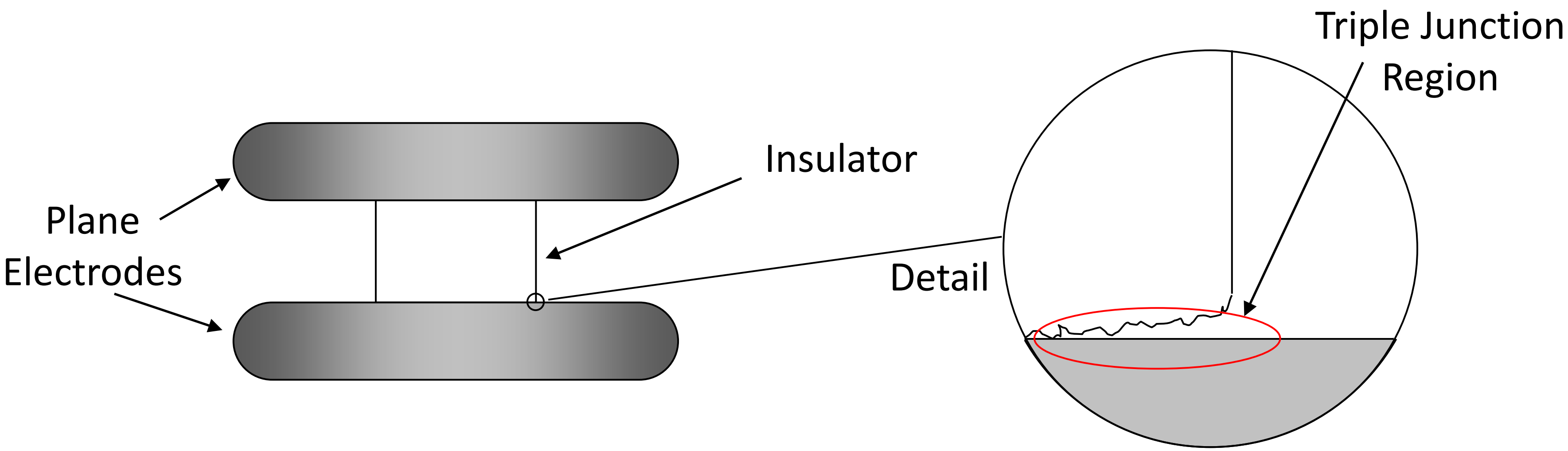
Charge Distribution

+36 kV Impulse

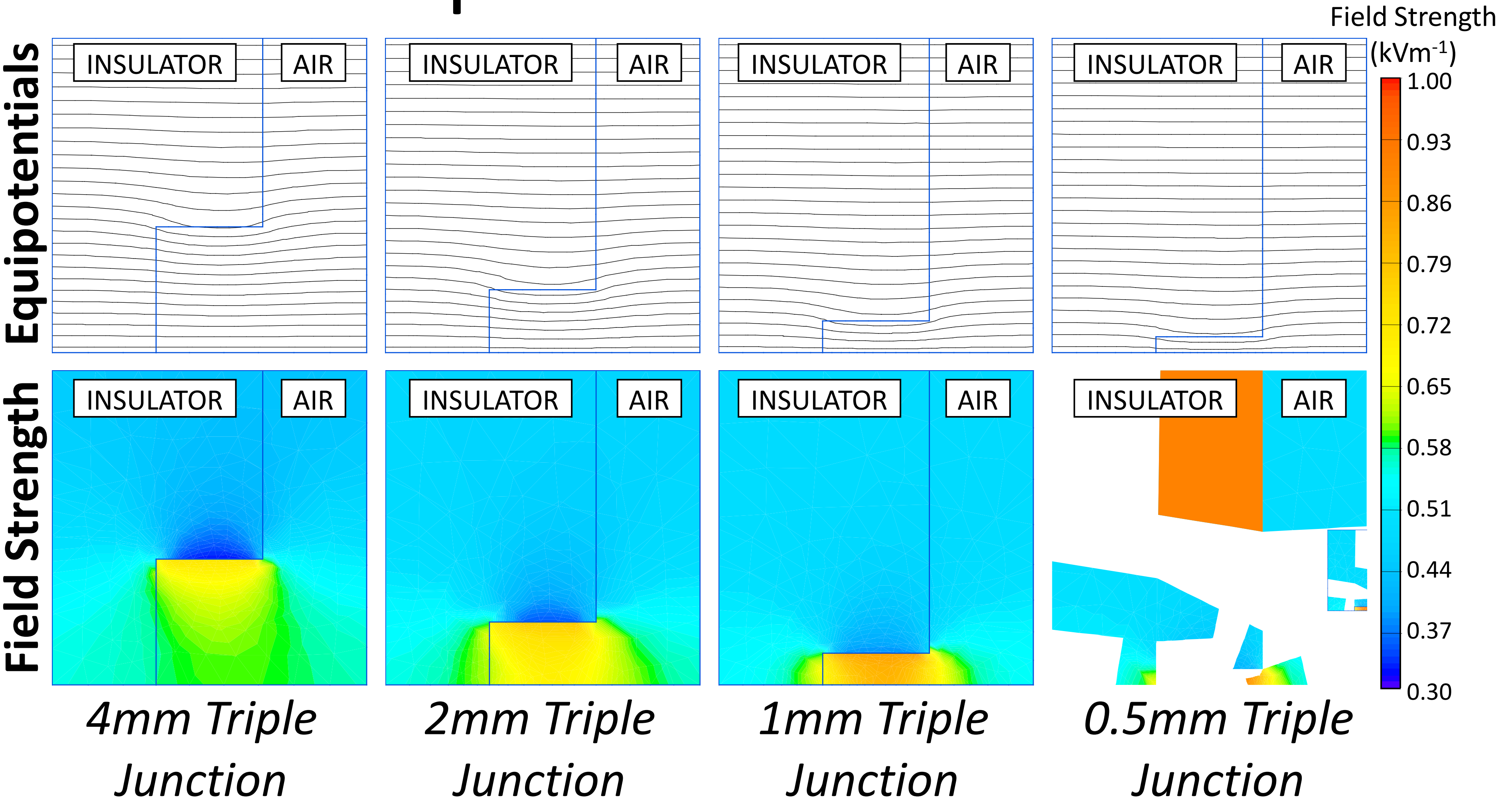
-70 kV Impulse

Polarity is very important if the gap is asymmetrical

Triple junctions always exist at some scale

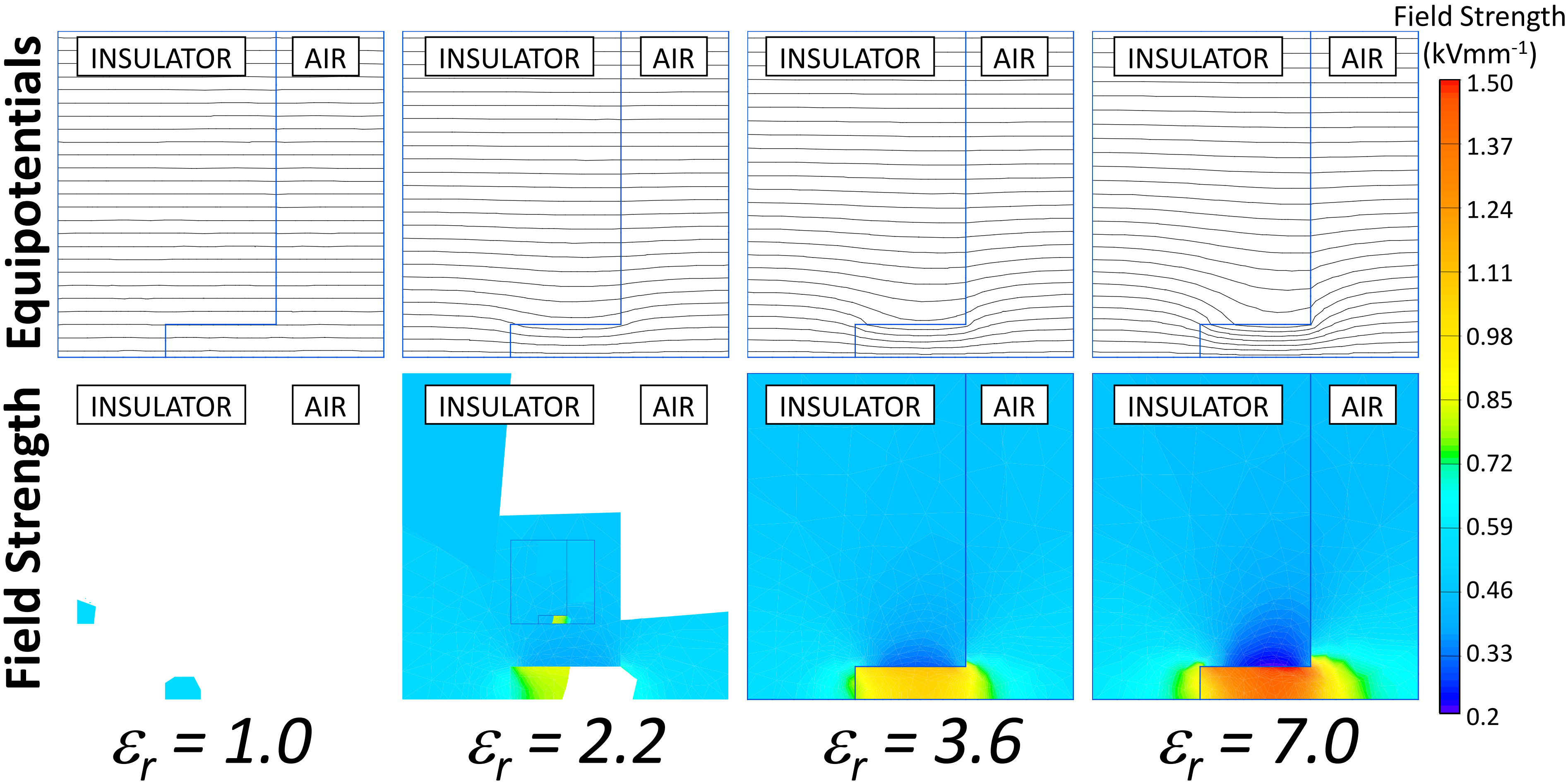


Triple Junction Effect



PTFE ($\varepsilon_r = 2.2$) ambient field of 0.5 $kVmm^{-1}$

Triple Junction Effect



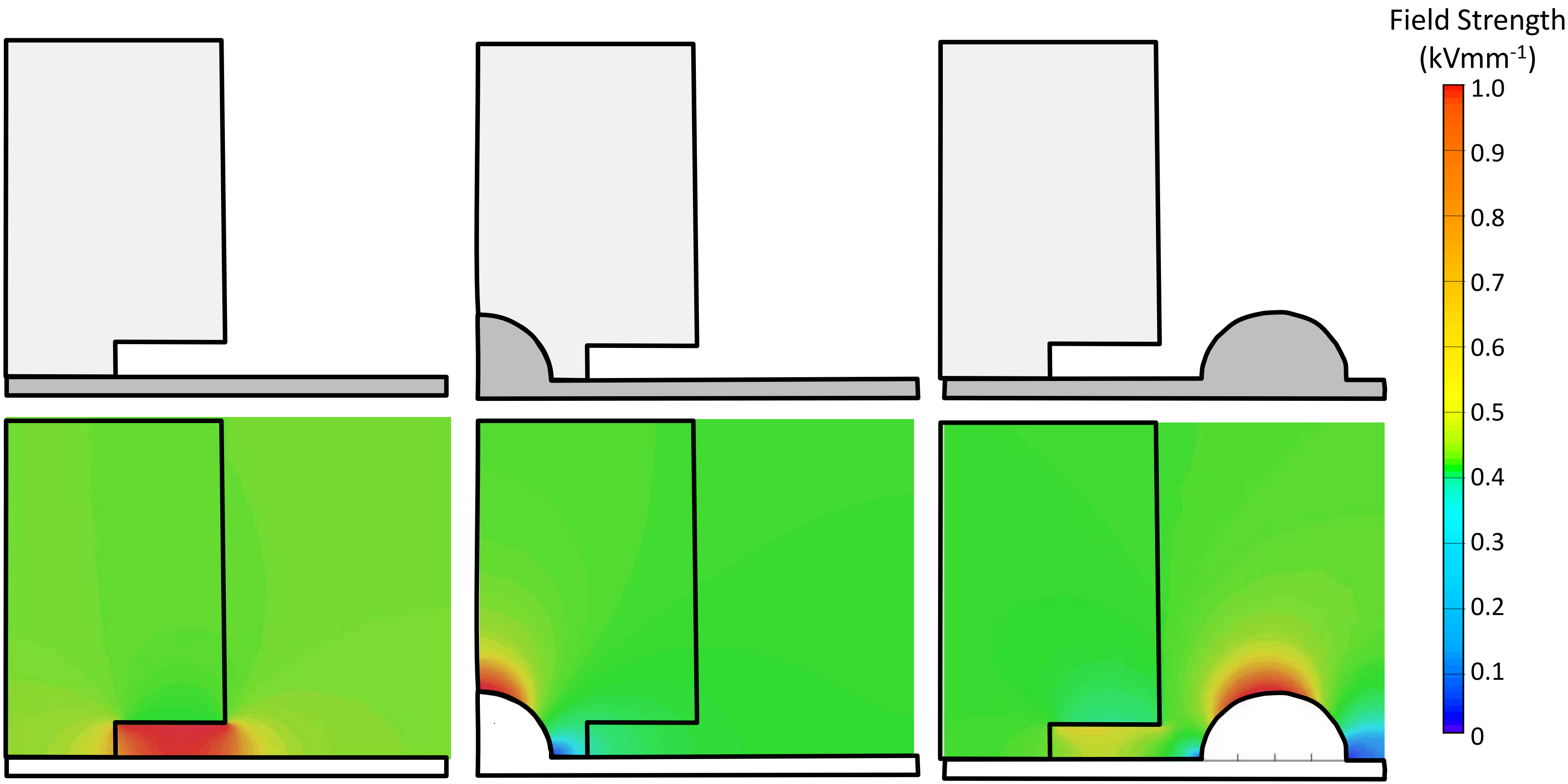
1mm triple junction ambient field of 0.5 $kVmm^{-1}$

Common Insulators

Material	Relative Permittivity, ε_r	Dielectric Strength (kV/mm)
Air	1	3
PTFE	2.2	19.7
Al_2O_3	8-10	13.4
Mica	6	118
Epoxy Resin	3.6	20
SF6	1.002	7.5
Oil	2.5 - 4	10 - 15

Triple Junction Screening

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



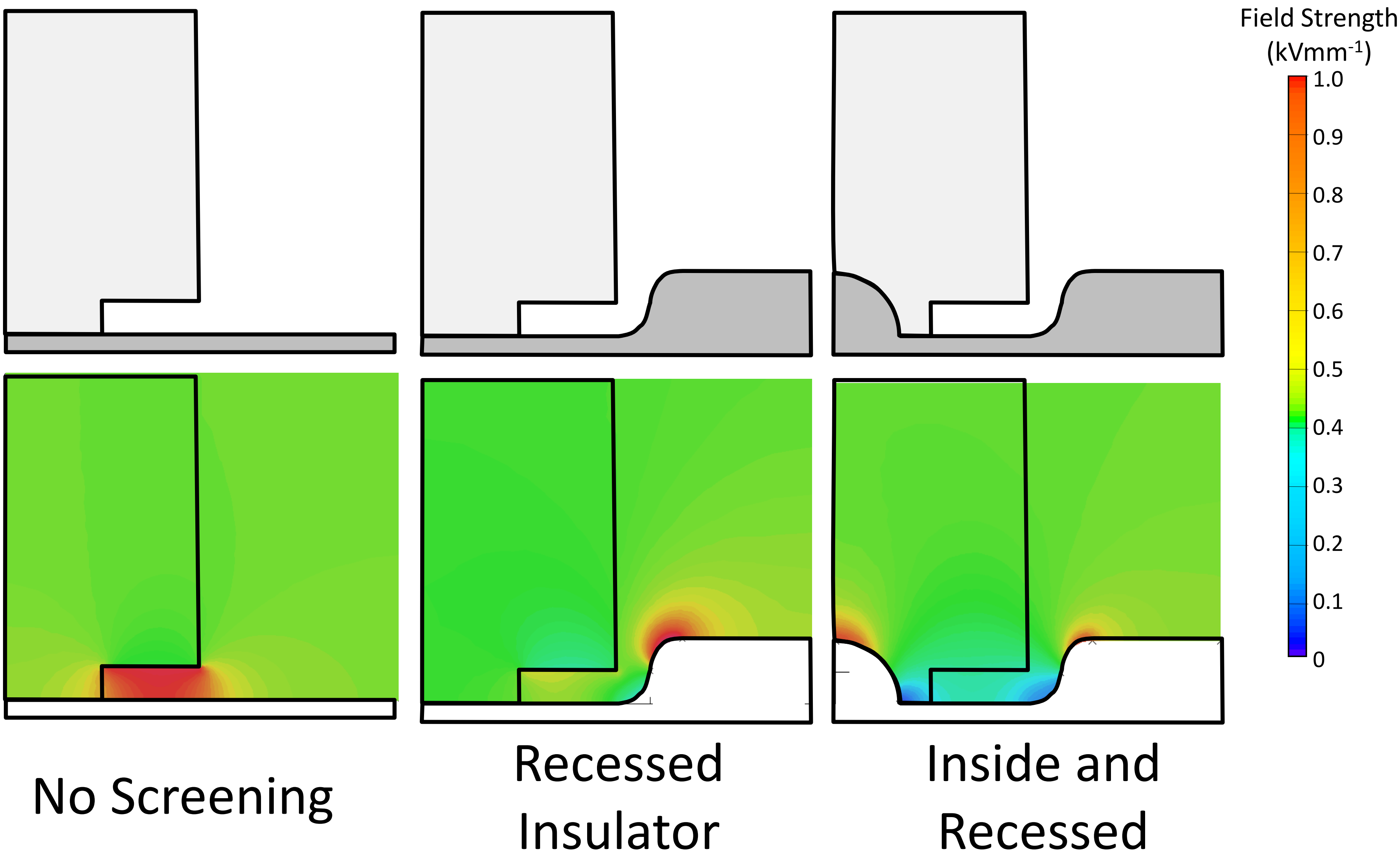
No Screening

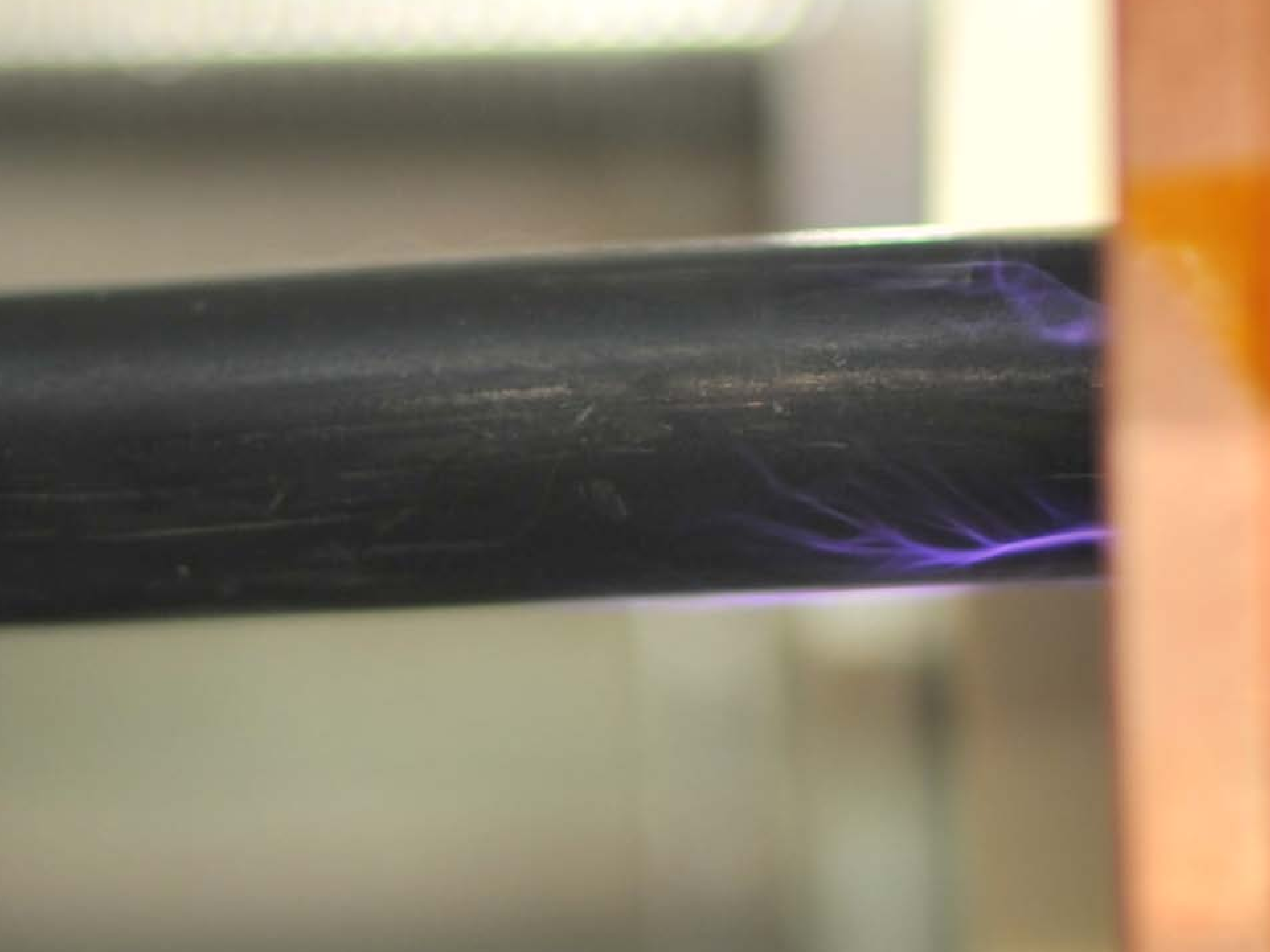
Inside Insulator

Outside Ring

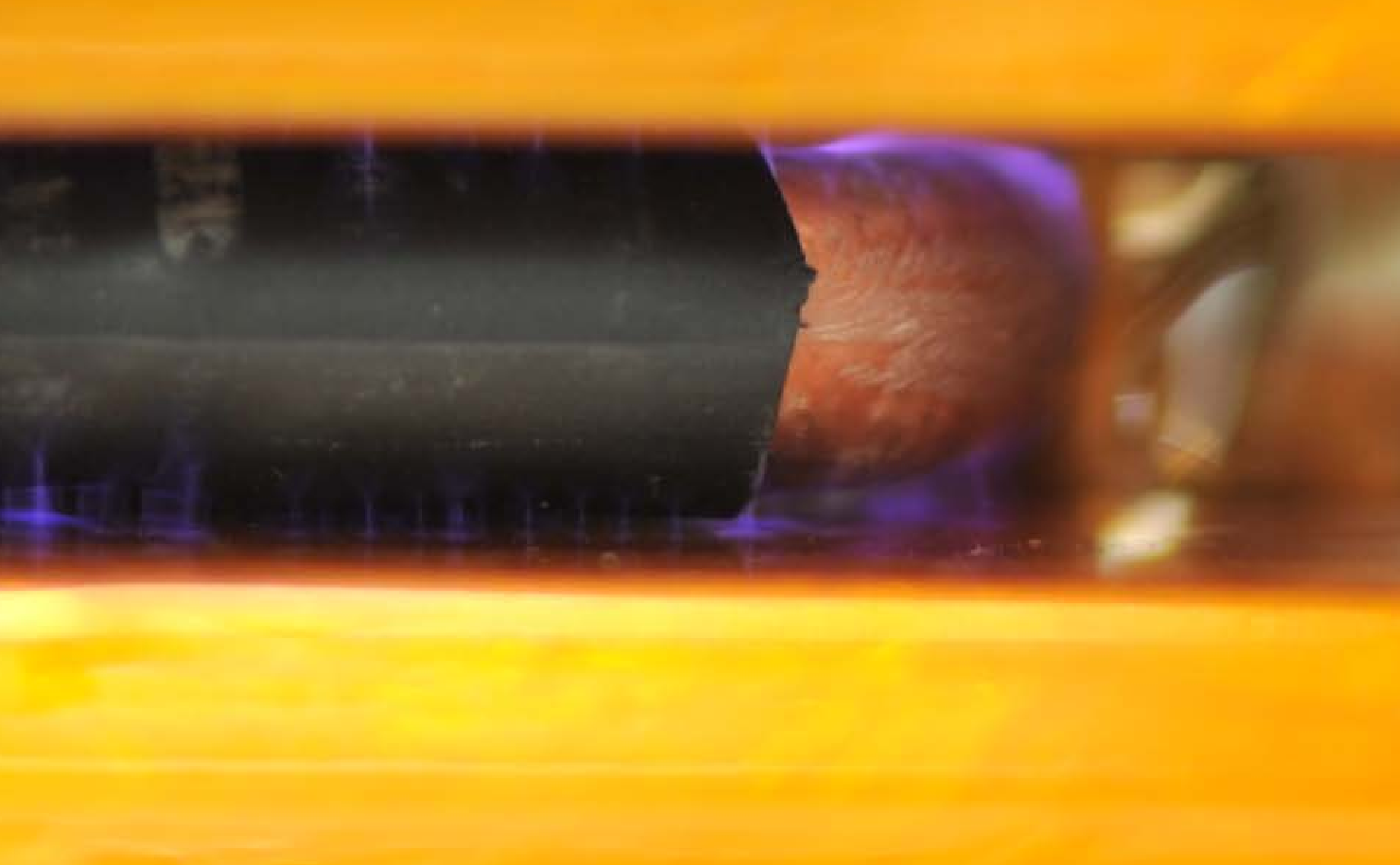
Triple Junction Screening

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

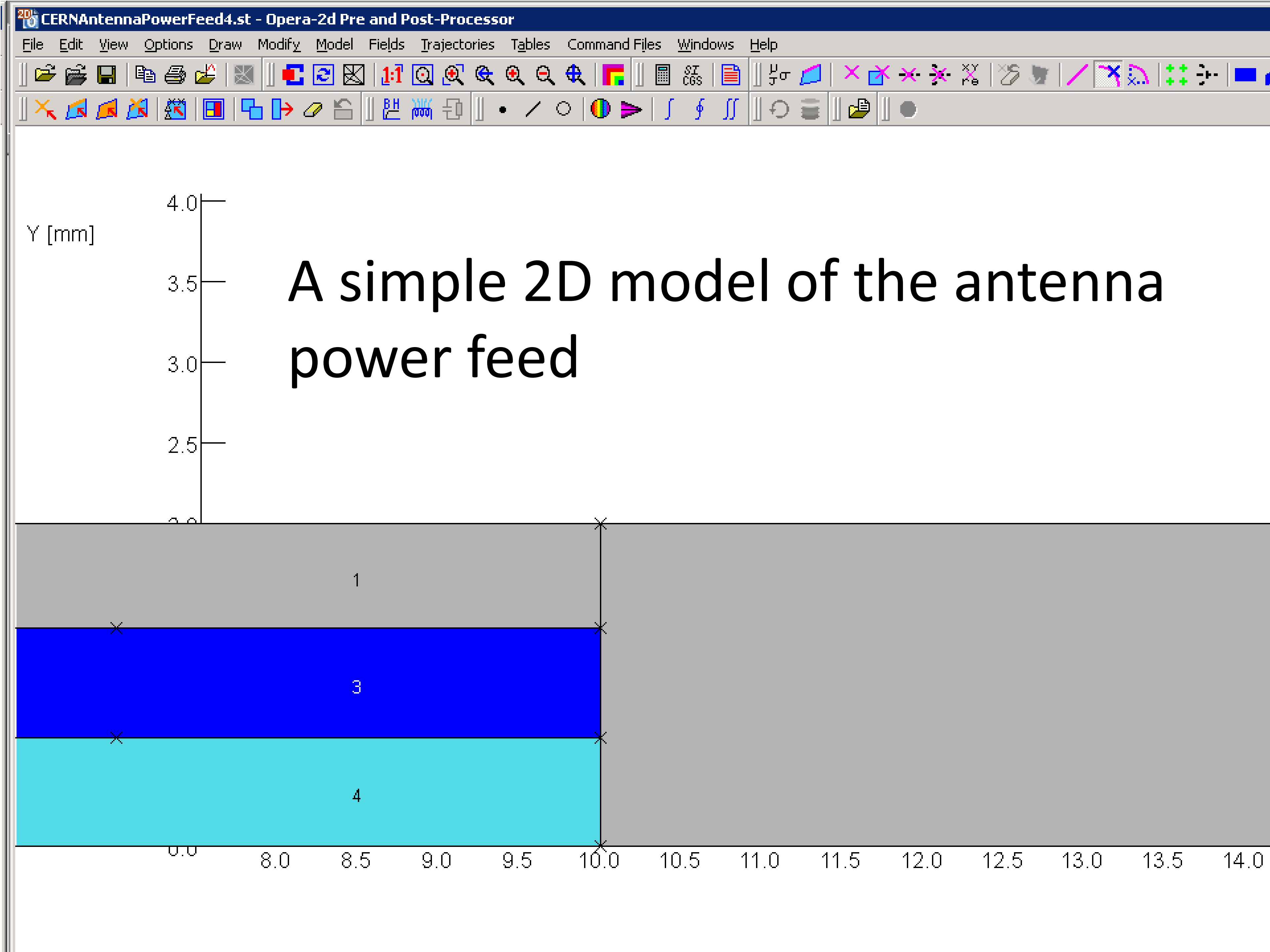




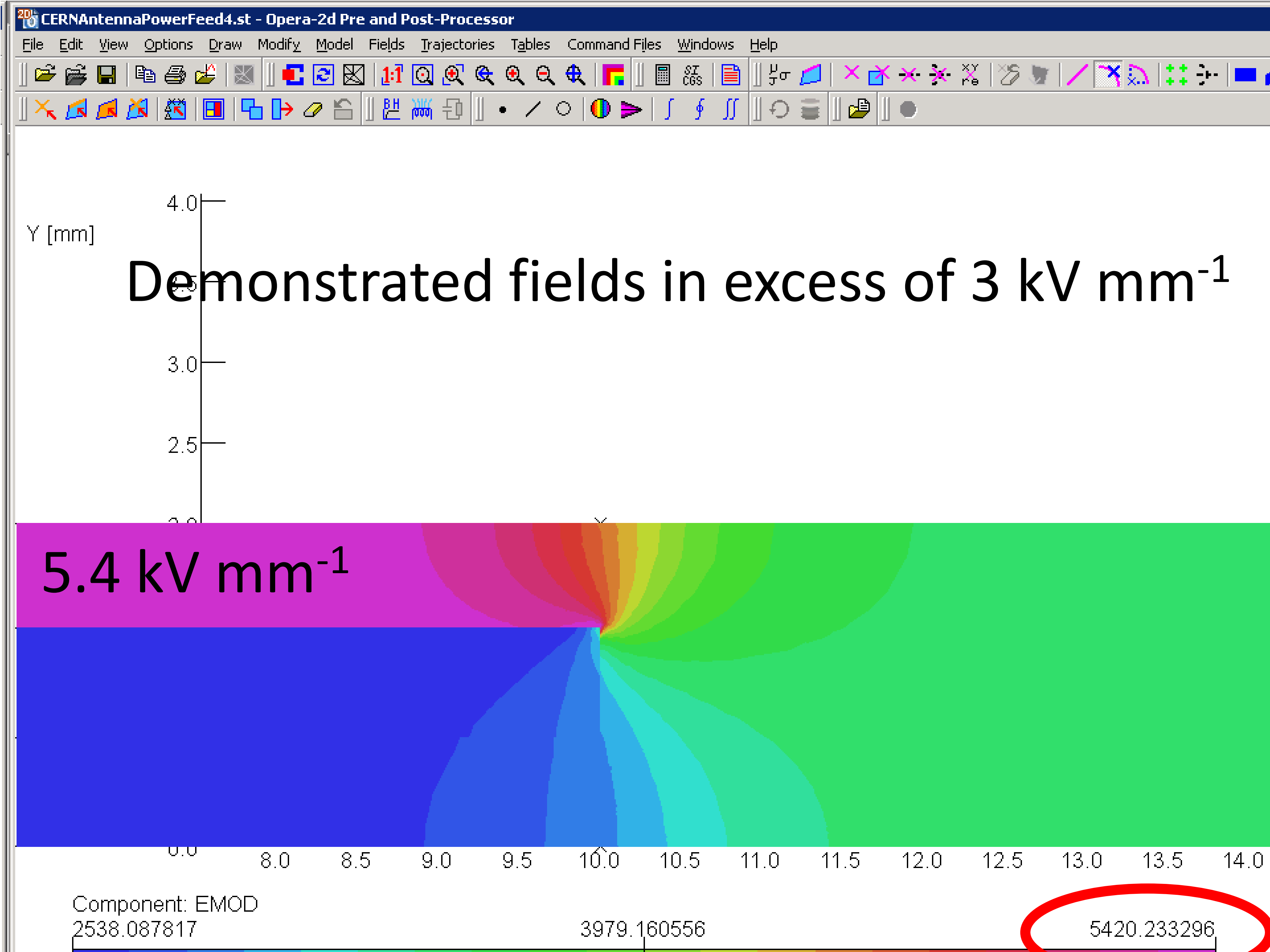
Antenna power feed sparking



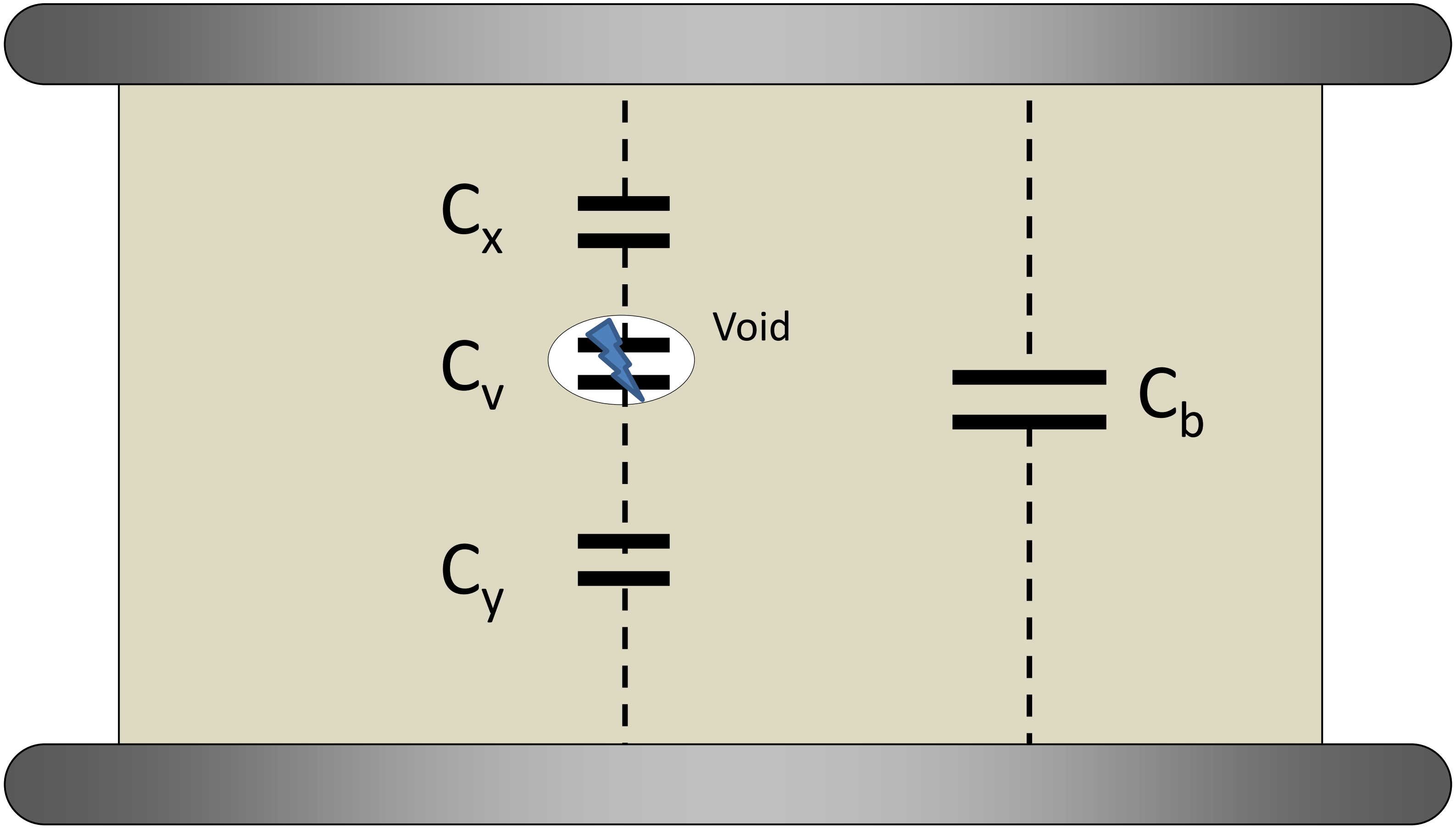
A simple 2D model of the antenna power feed



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



Partial Discharges



Insulator Materials

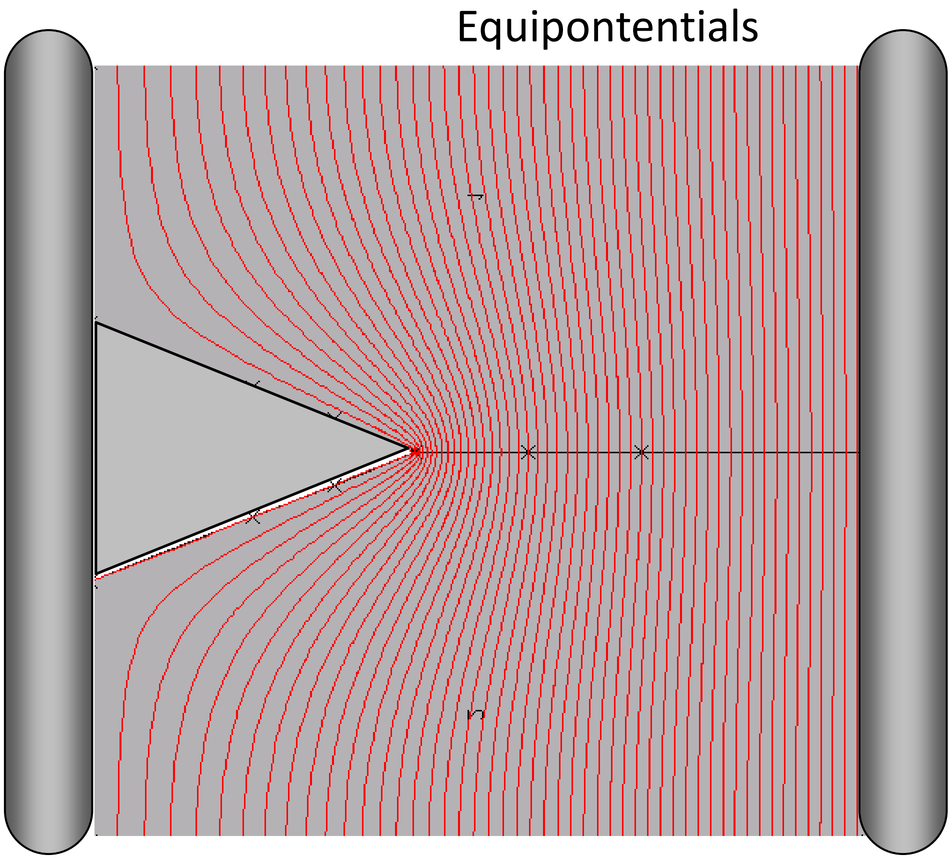
Depends on application!

For example:

Al_2O_3 is commonly used in sources 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

Corona

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



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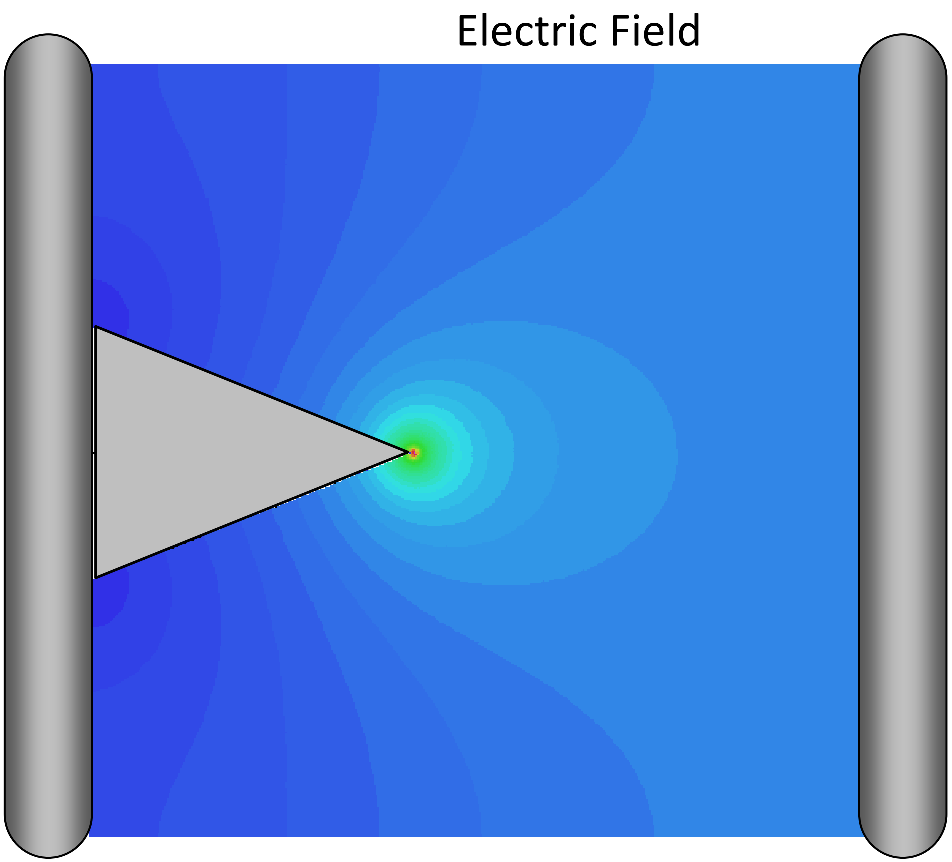
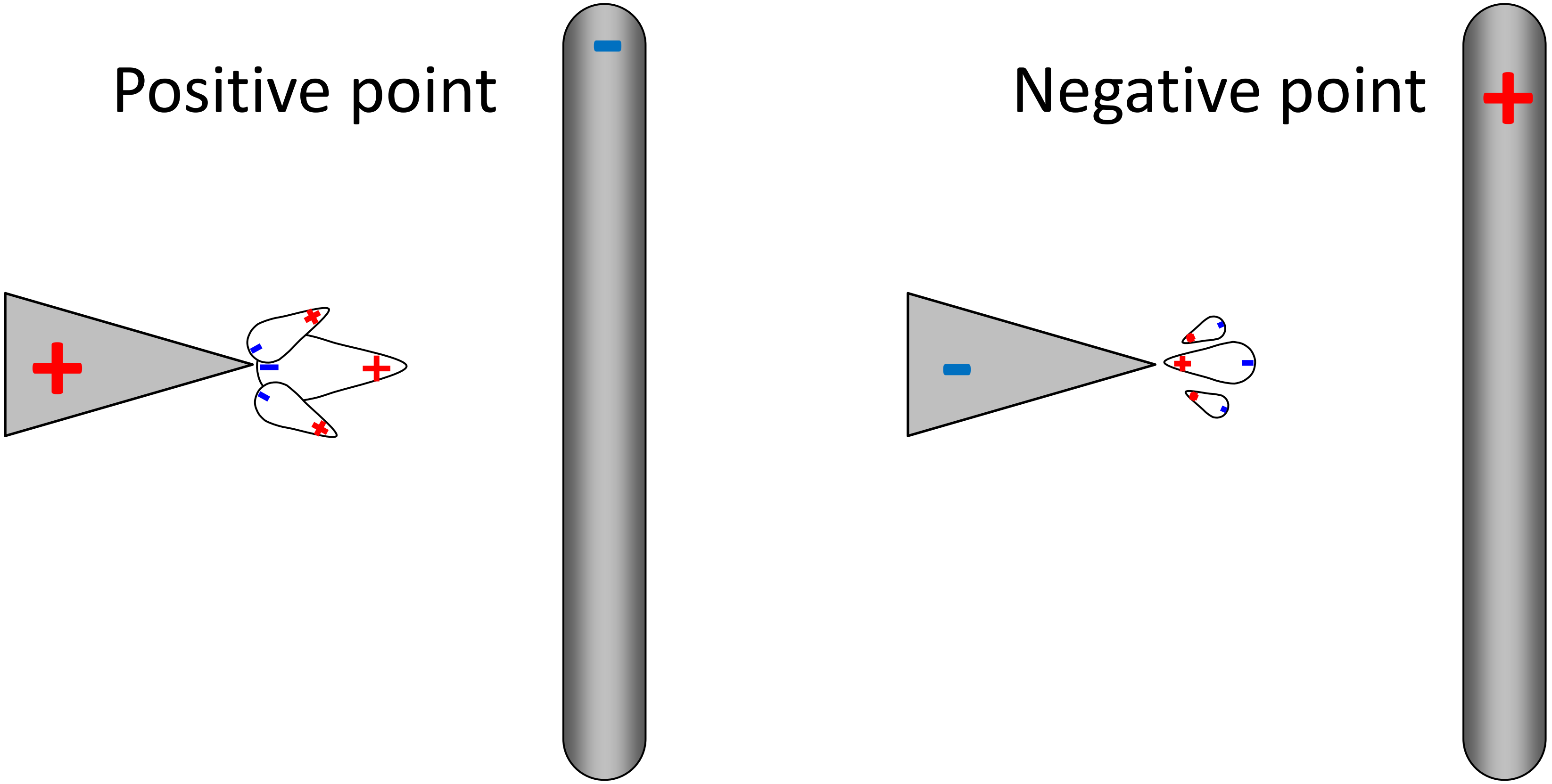


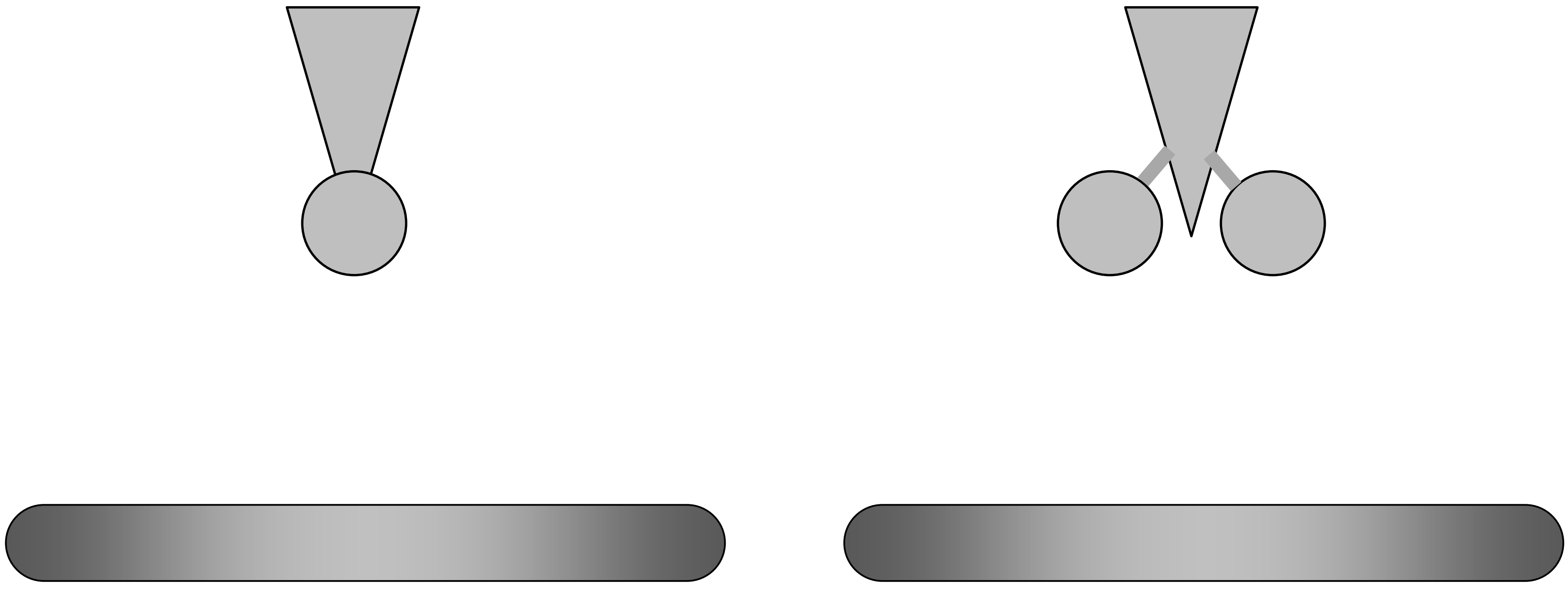
Corona

- Corona is another type of partial discharge occurring in very 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



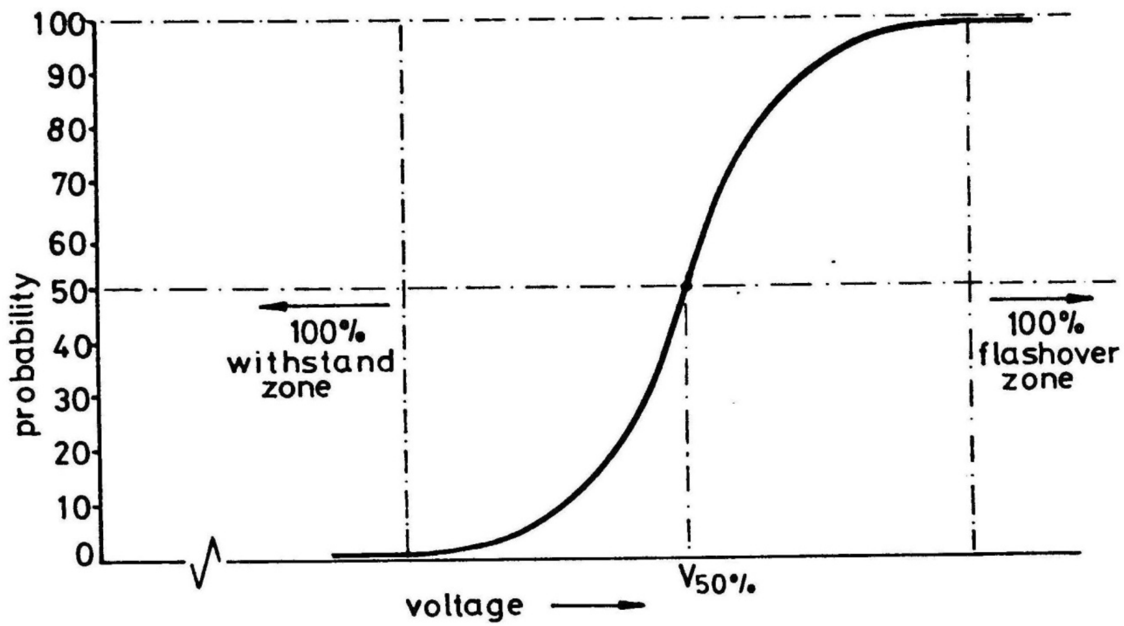
Breakdown strength of Air

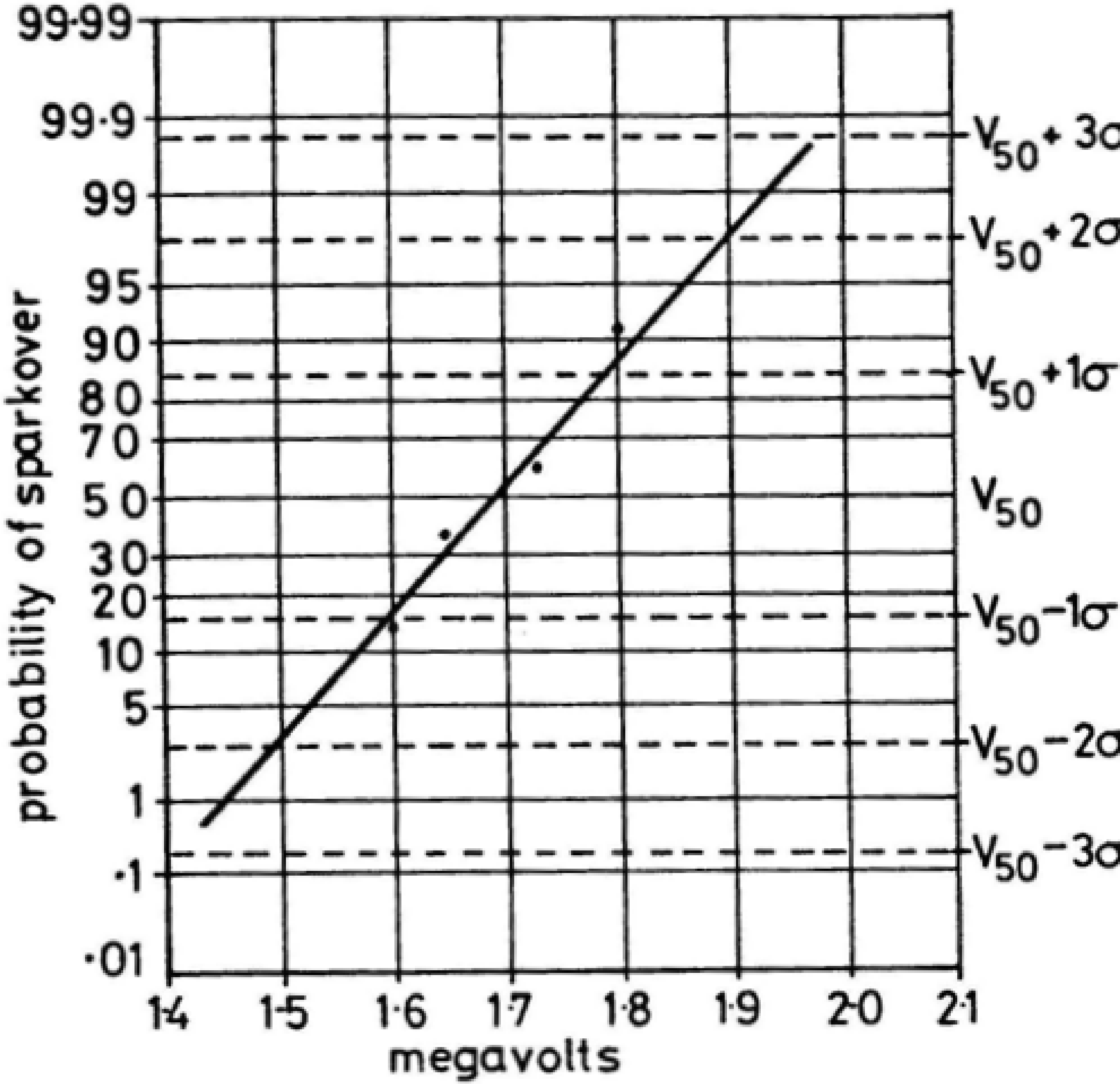
In air at normal room conditions two electrodes require about 30 kV for each cm of spacing to breakdown (as a rule of thumb)

Or 3 $kVmm^{-1}$

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
1·4
1·5
1·6
1·7
1·8
1·9
2·0
2·1
megavolts
$V_{50}+3\sigma$
$V_{50}+2\sigma$
$V_{50}+1\sigma$
V_{50}
$V_{50}-1\sigma$
$V_{50}-2\sigma$
$V_{50}-3\sigma$

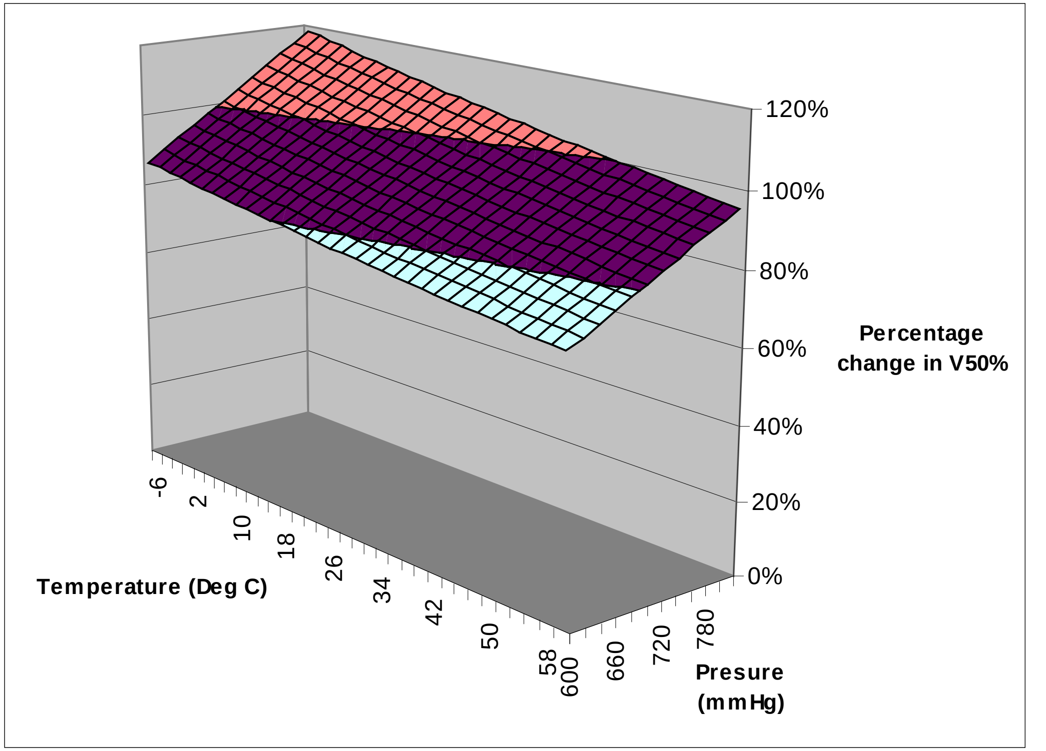
Environmental conditions

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

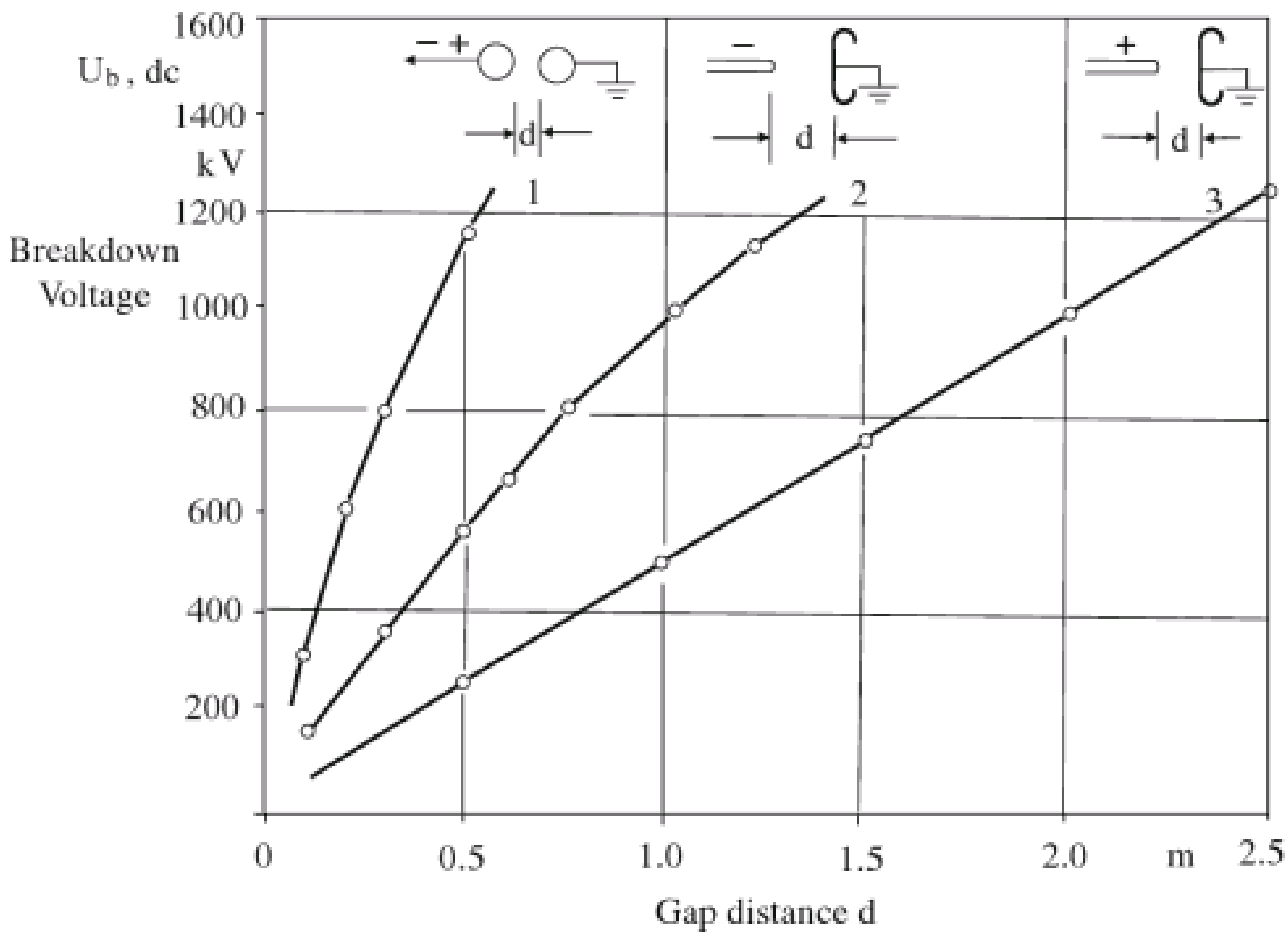
$$\frac{0.386 \times P}{273 + t}$$

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

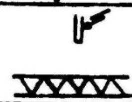
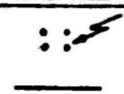
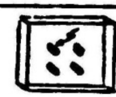
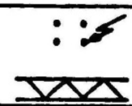
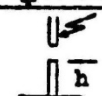
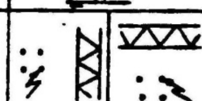
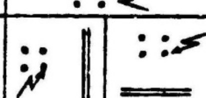
Humidity can also affect breakdown voltage

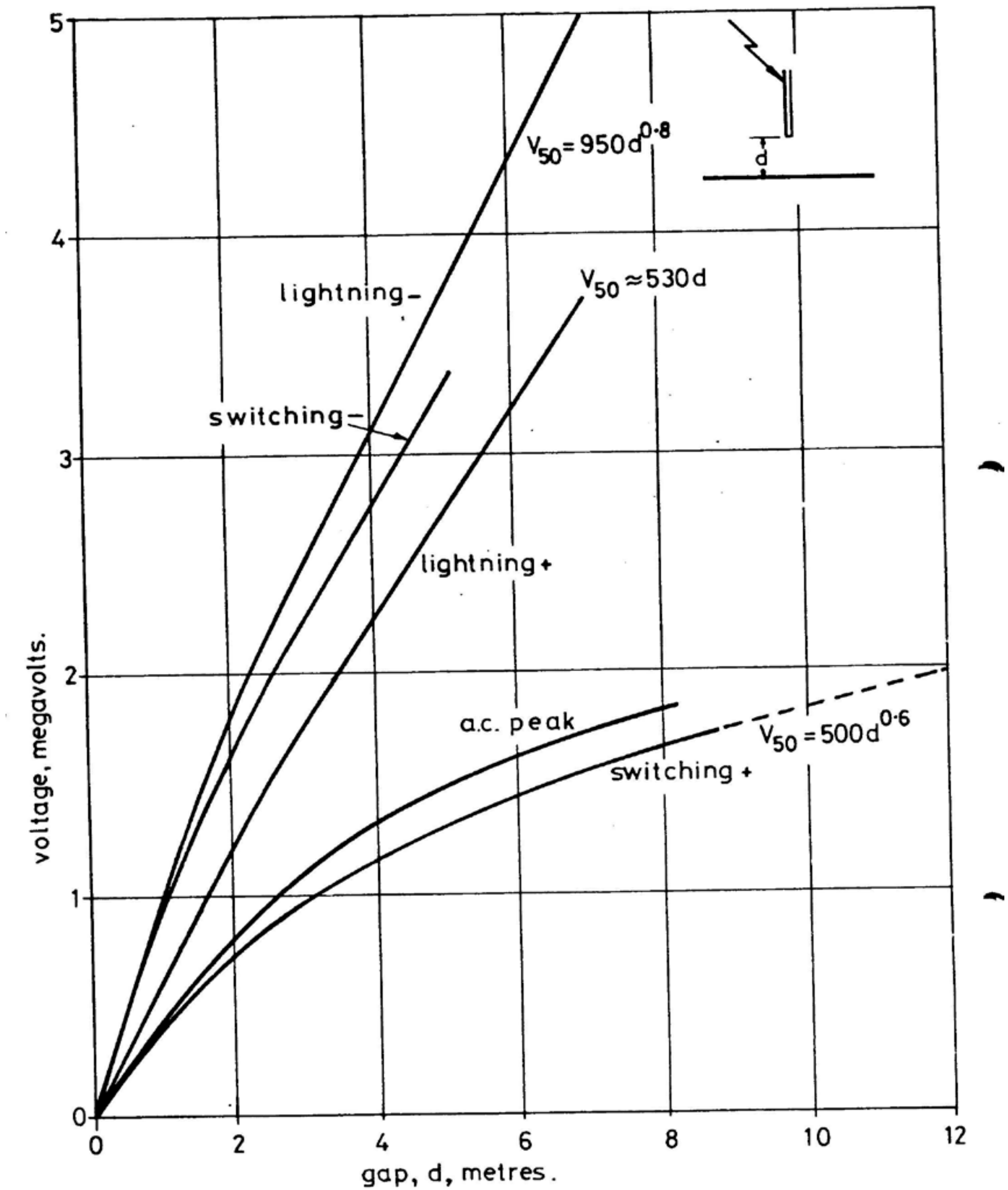


Polarity is important in Non Uniform Gaps



Geometry Scaling factors

	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



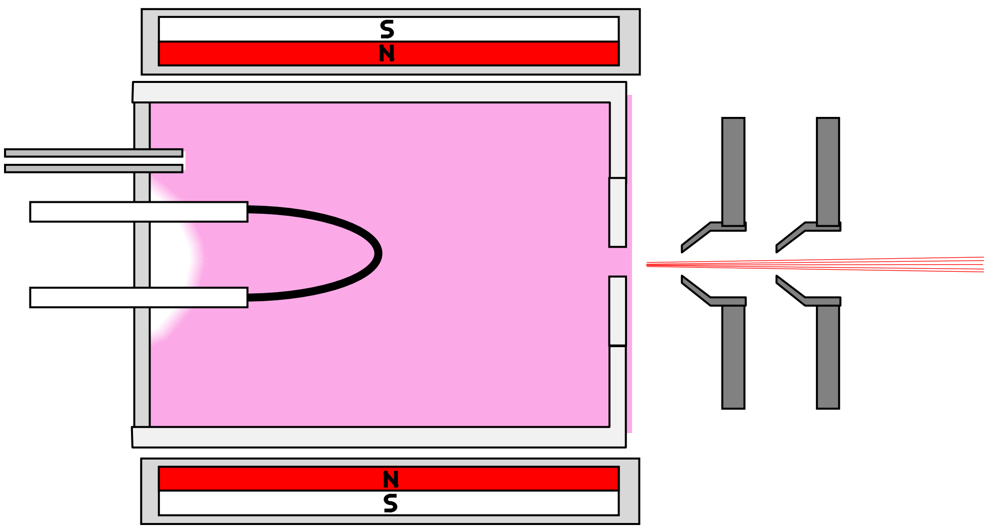
Type of Applied Voltage is Important

Additional Complications

- Magnetic Fields
- Xrays
- Space charge
- Insulator surface charge
- Stray beam
- Contamination

High Voltage Design

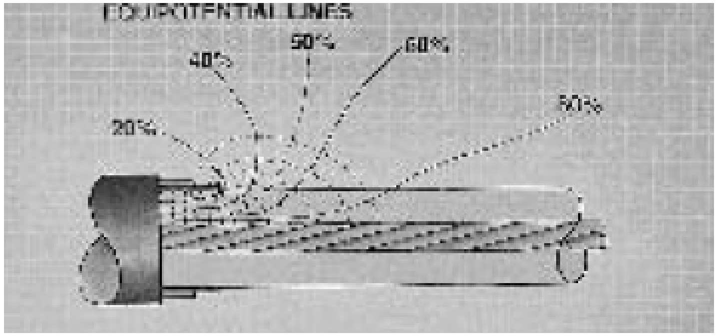
High voltage platform or internal isolation?

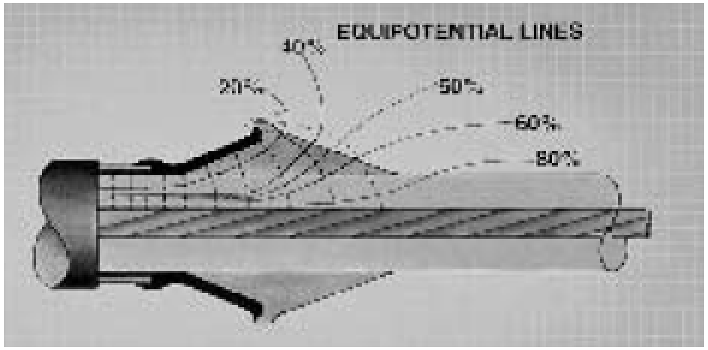


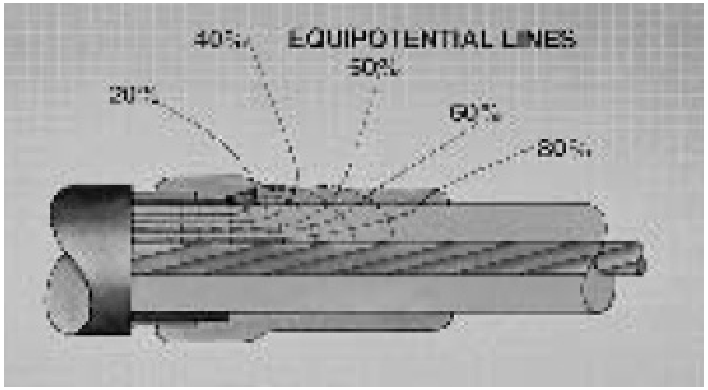
Pros and cons

Cables and Terminations

Correct termination of high voltage cables is essential







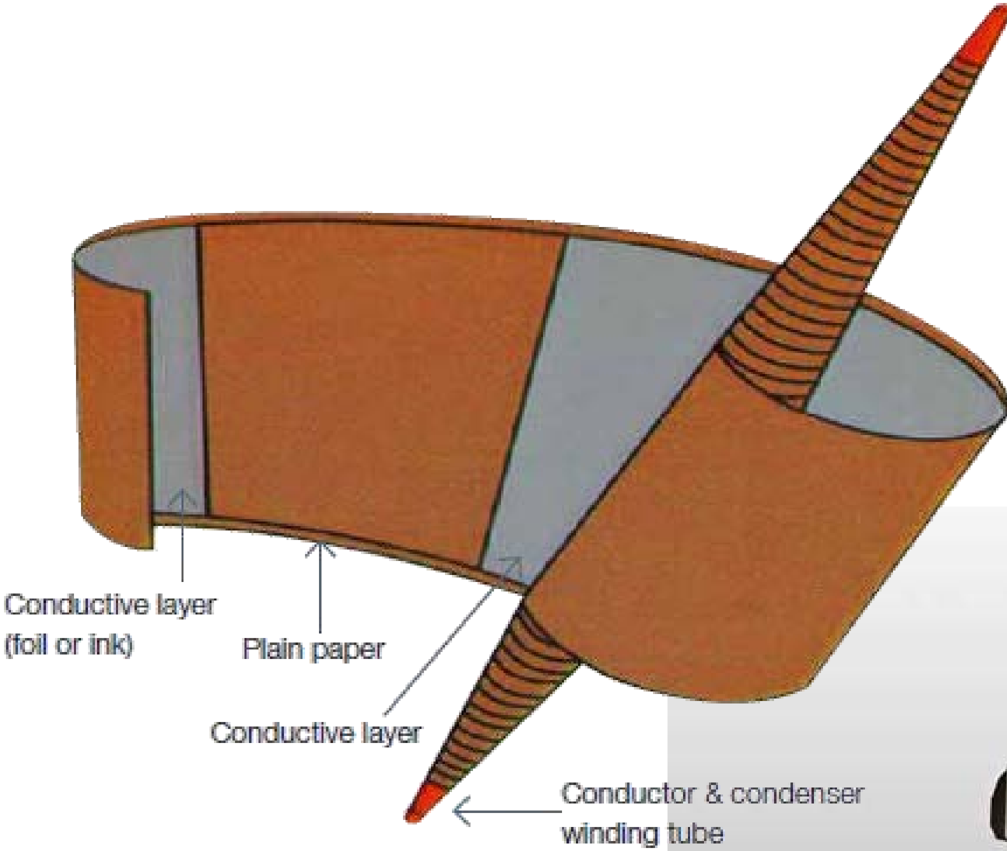
Connectors or Bushings?

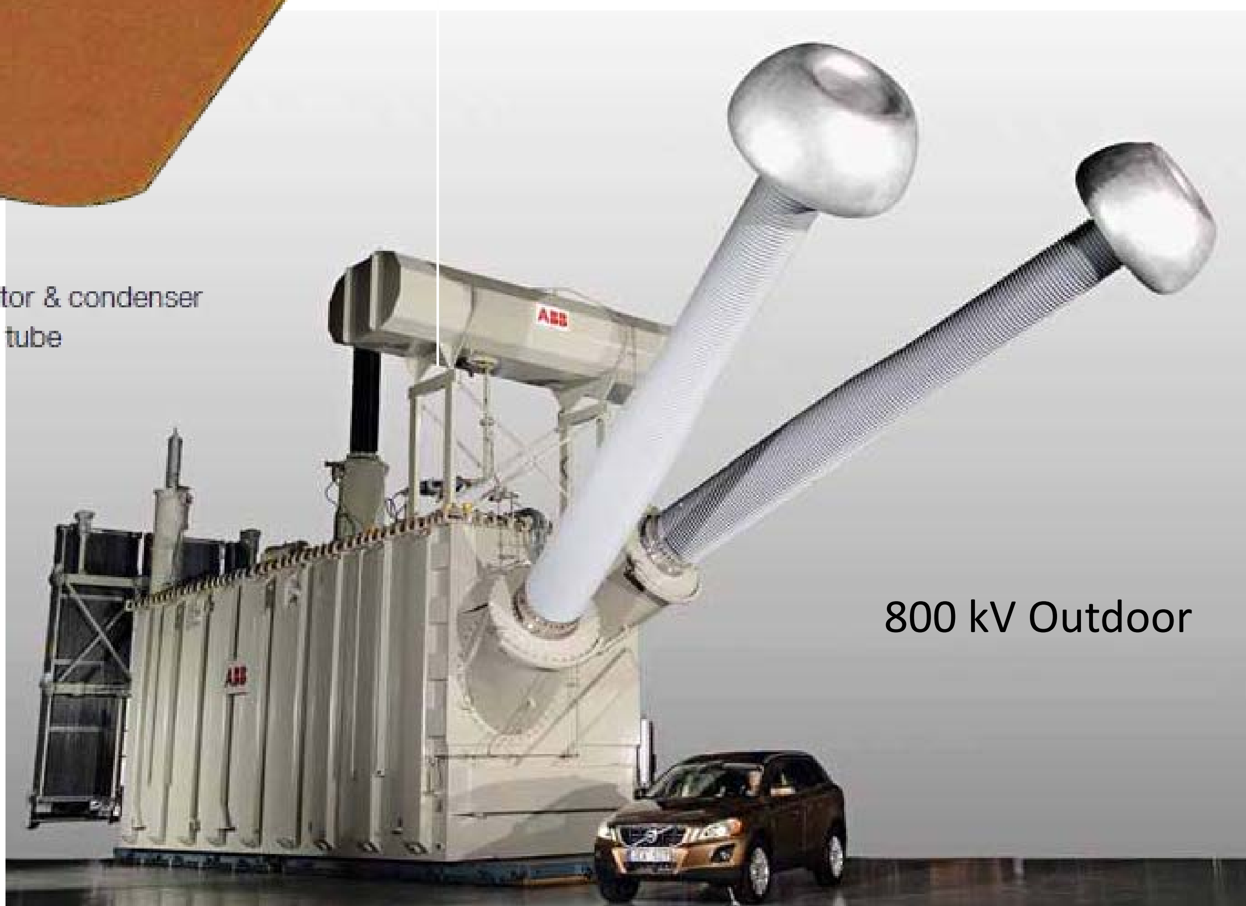
Depends on...

- Application
- Maintenance
- Permanence


OUTPUT TO ION
SOURCE EXTRACTOR

Big Bushings





Commercial Insulators

- Dirt and Dust
- Sheds
- Tracking

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...


Beard
Partners in Construction


BEAM ON
EARTHED
HT ON
EMERGENCY LOWERING

Clean lab conditions!

Water and home-made insulators don't mix

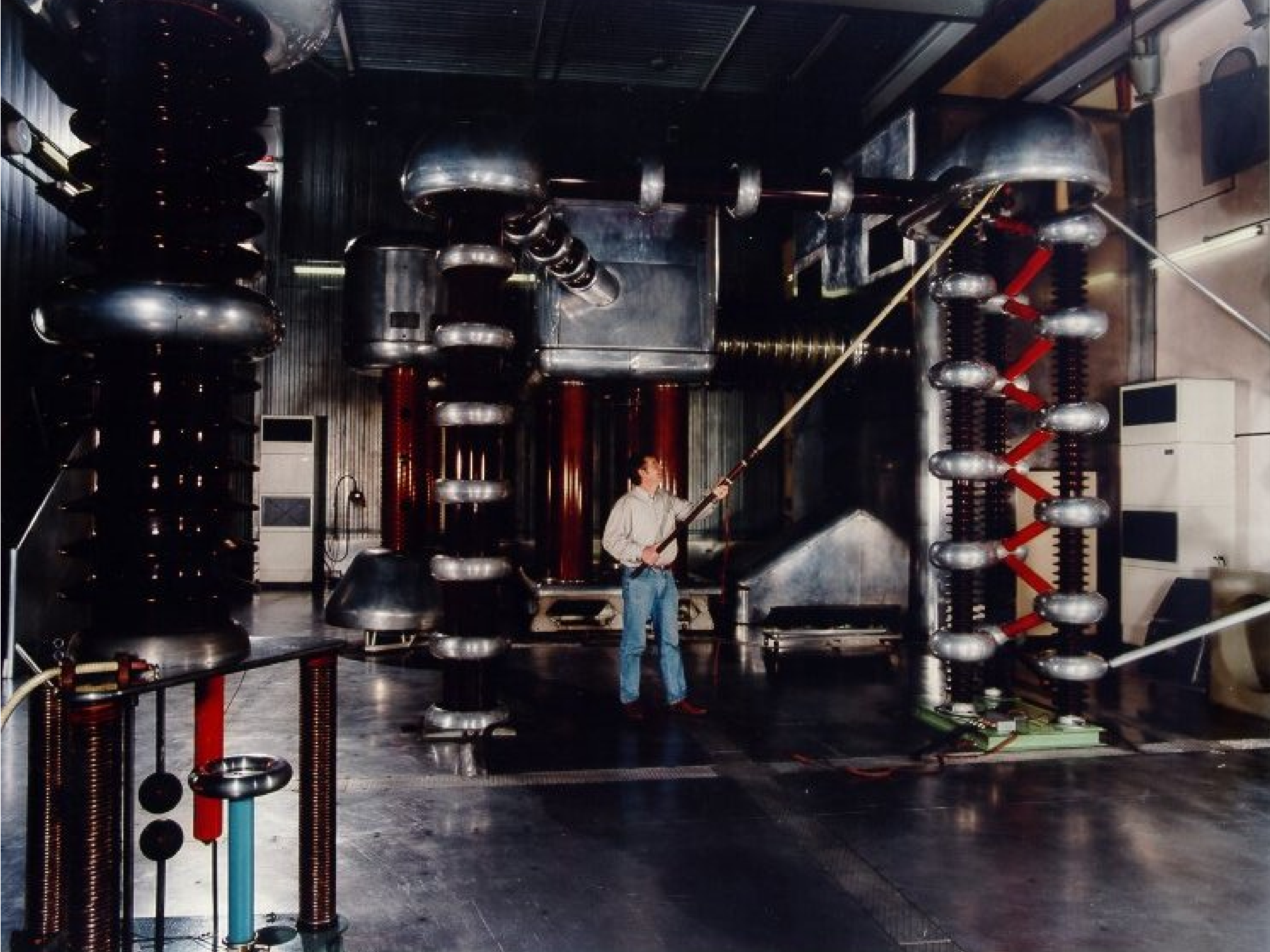

XL

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

Power to the Platform

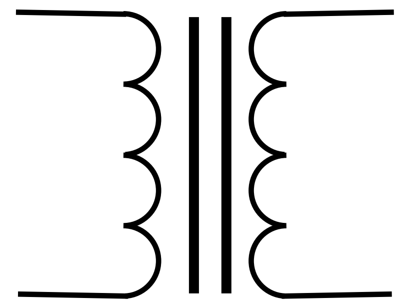
How to get power to the equipment on the HV platform?

- Motor alternator set
- Isolating transformer
- Waveguide DC break



Solid Insulation Isolation Transformer

1:1



Oil Filled Isolation Transformer

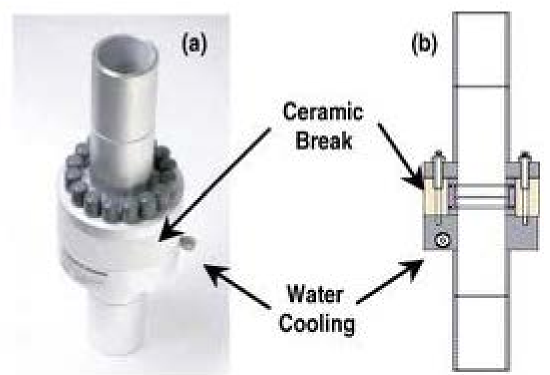
Oil dielectric strength
10 – 15 $kVmm^{-1}$

Pro: Compact design
Con: Bund required

RF Waveguide DC Breaks

Air

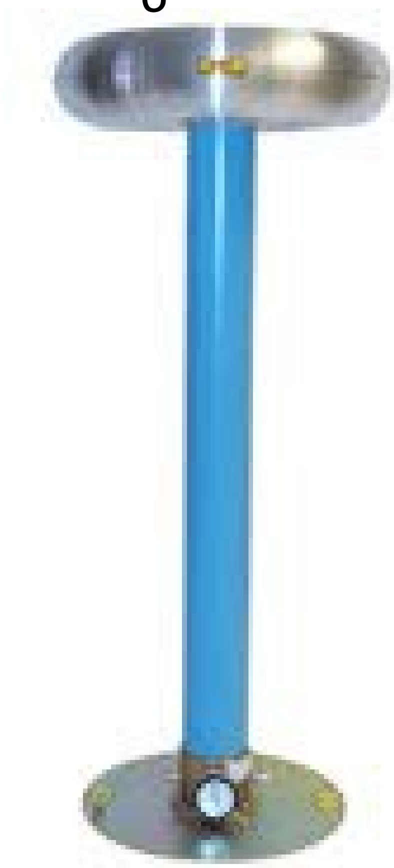
Vacuum



Water Cooled

Voltage Dividers

SF_6 Filled



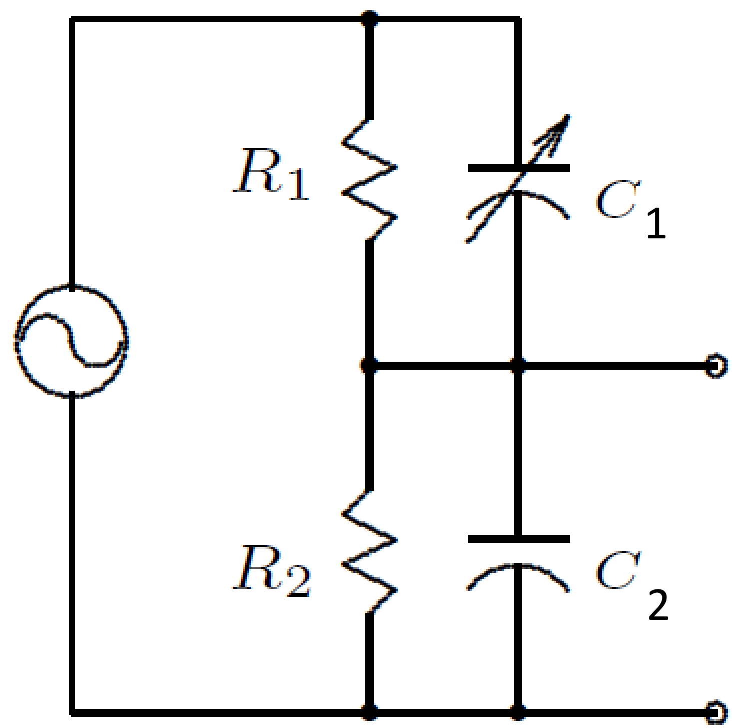
Compensated

$$K = \frac{Z_2}{Z_1 + Z_2}$$

If $R_1C_1 = R_2C_2$

$$K = \frac{R_2}{R_1 + R_2}$$

For all frequencies



SF_6 dielectric strength 2.5 times air = 7.5 $kVmm^{-1}$

Insulation Test Equipment

Current limited test of insulation withstand strength

Power Supply Technologies

- Semiconductors: Thyristor, IGBT, GTO
- Tube- tetrode
- PFN
- Cascade rectifier (Greinacher/ Cockcroft–Walton multiplier)
- Vandergraph, peloton
- Linear (Usually front end only)
- Switched mode-transformer -HV Diode and Capacitor

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

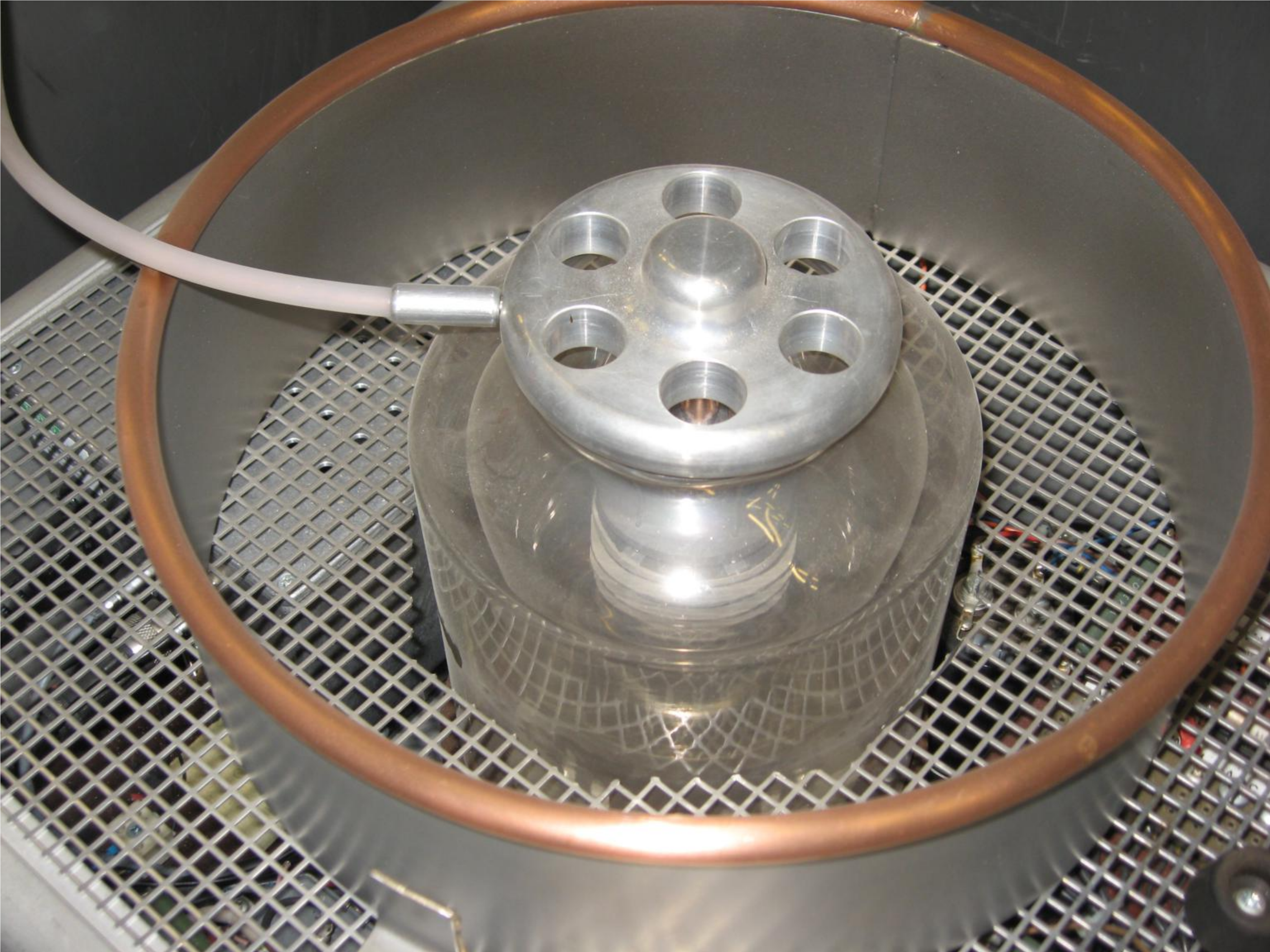
a.l.e. systems

Custom Built Power Supplies

- Tight specification is essential

- Or of course you could make your own if it is specialised e.g. pulsed extraction.

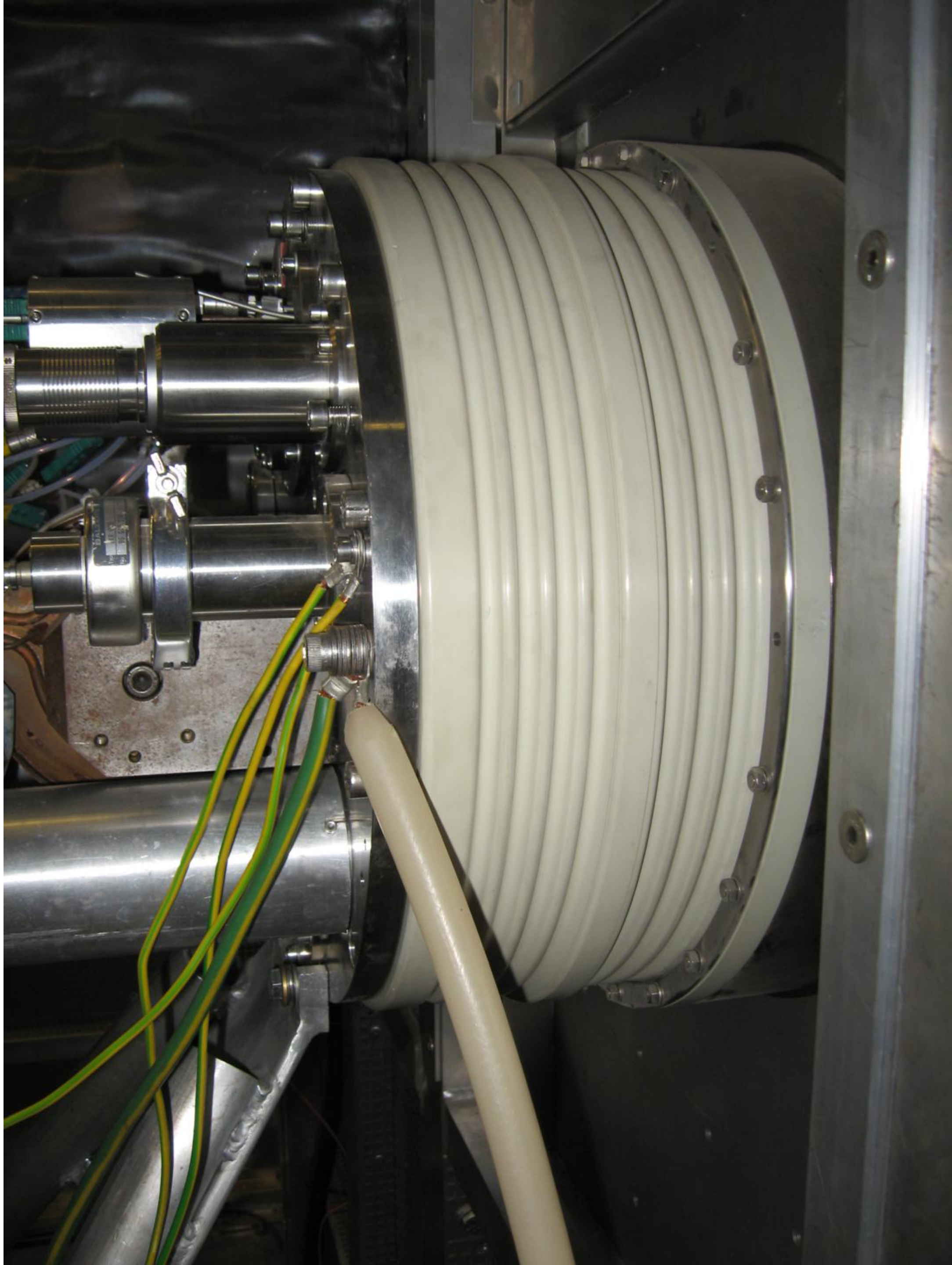
Tetrode used for ISIS 17 kV pulsed extraction power supply



Earthing

Solid single point earth

High voltage platform
"Local earth"



Safety

- Electric Shocks can kill
- Stored energy in capacitors

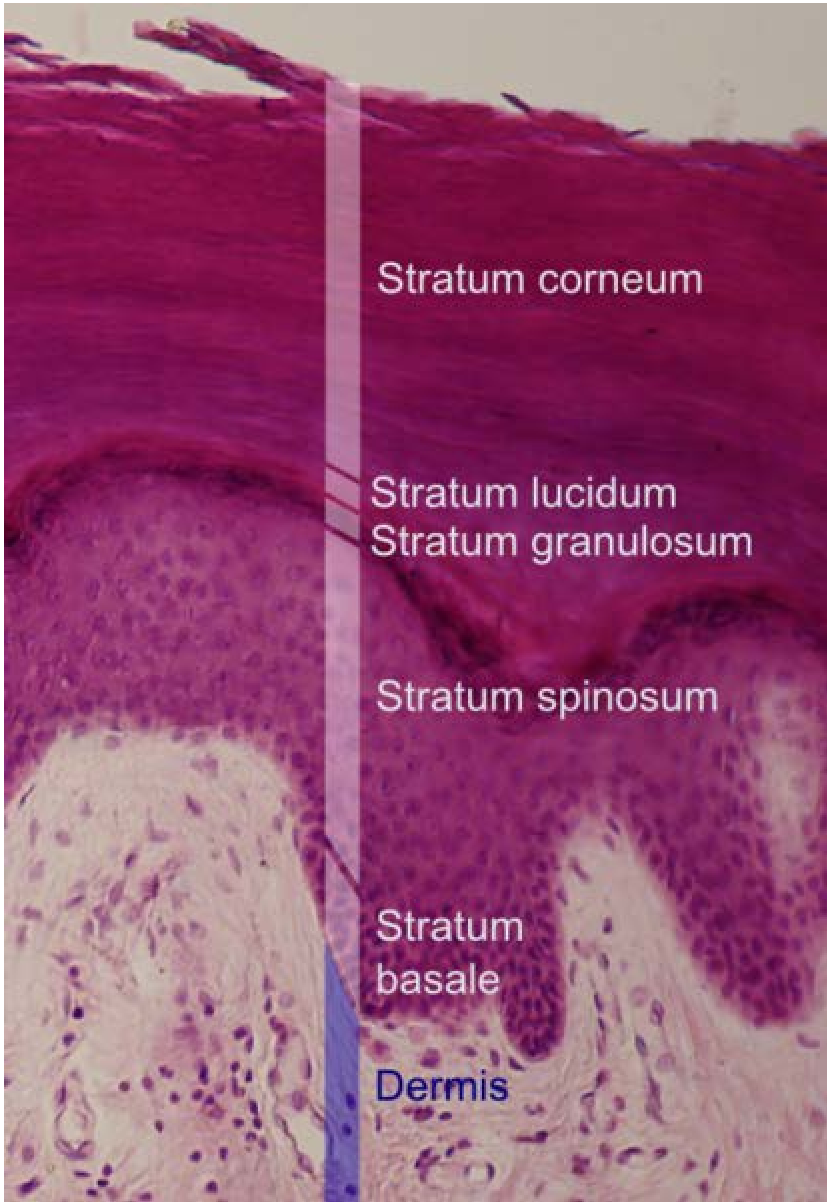
  $\frac{1}{2}CV^2$ = 0.5 x 1 μF x 30 kV = 450 J

- 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

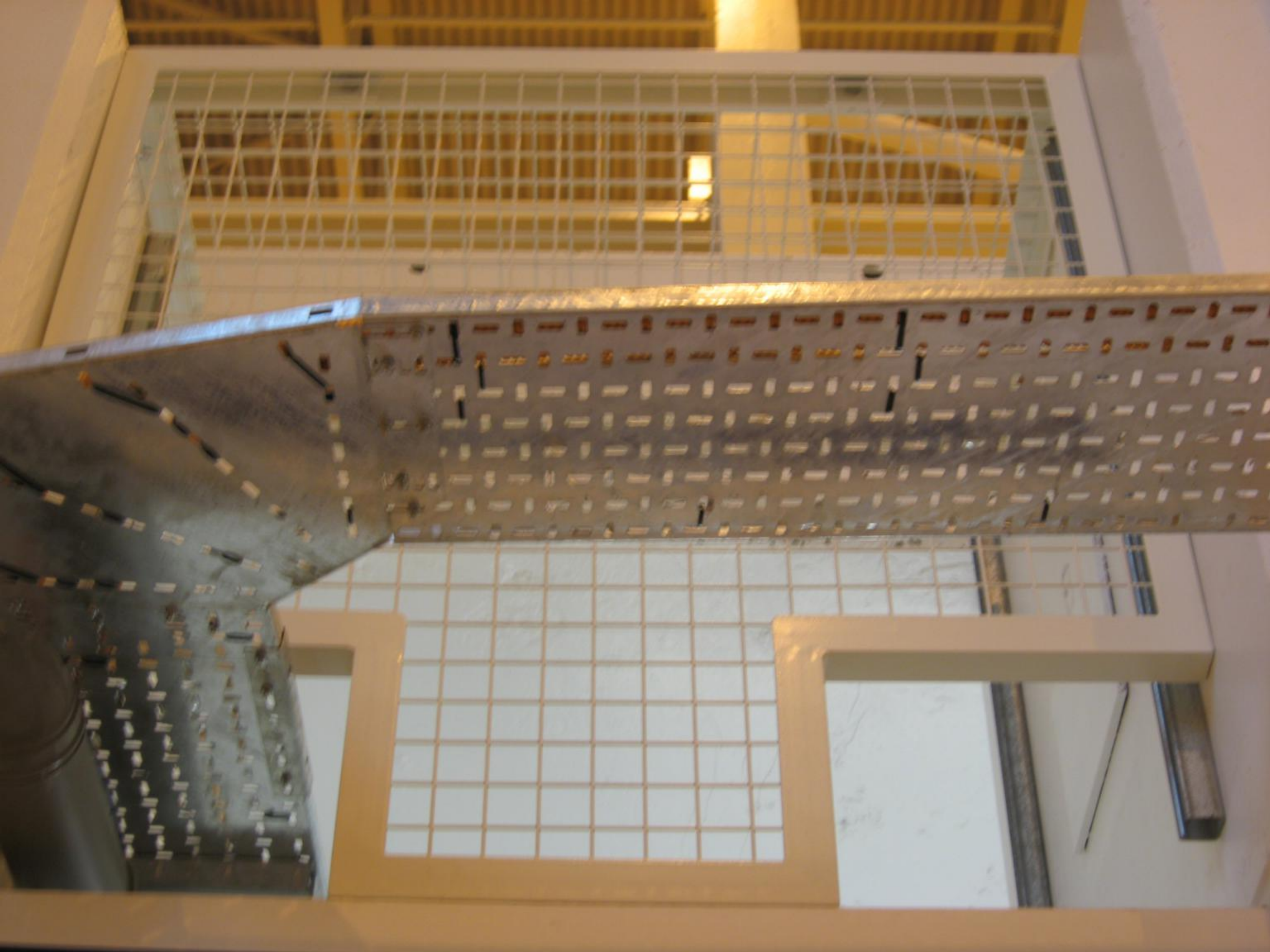


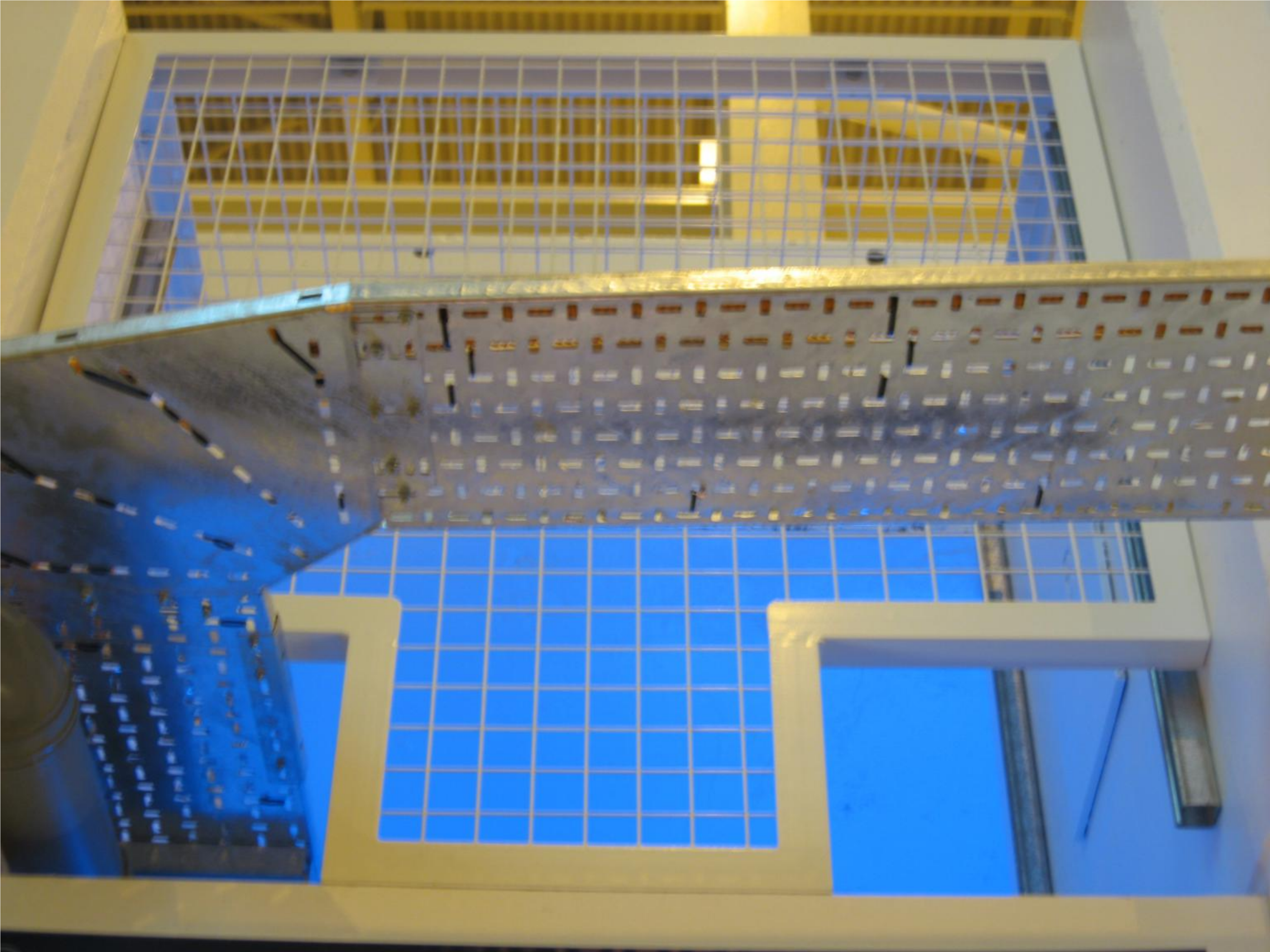
HV Safety Philosophy

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.


SEARCH


DMG






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

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.


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

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.


CS


CS


BIAS03


SONIAC VAULT
2314210


RADIATION ON
HV ON


Science & Technology Facilities Council
ISIS
The Ion Source Development Rig (ISDR
HT ON
EARTHED

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.
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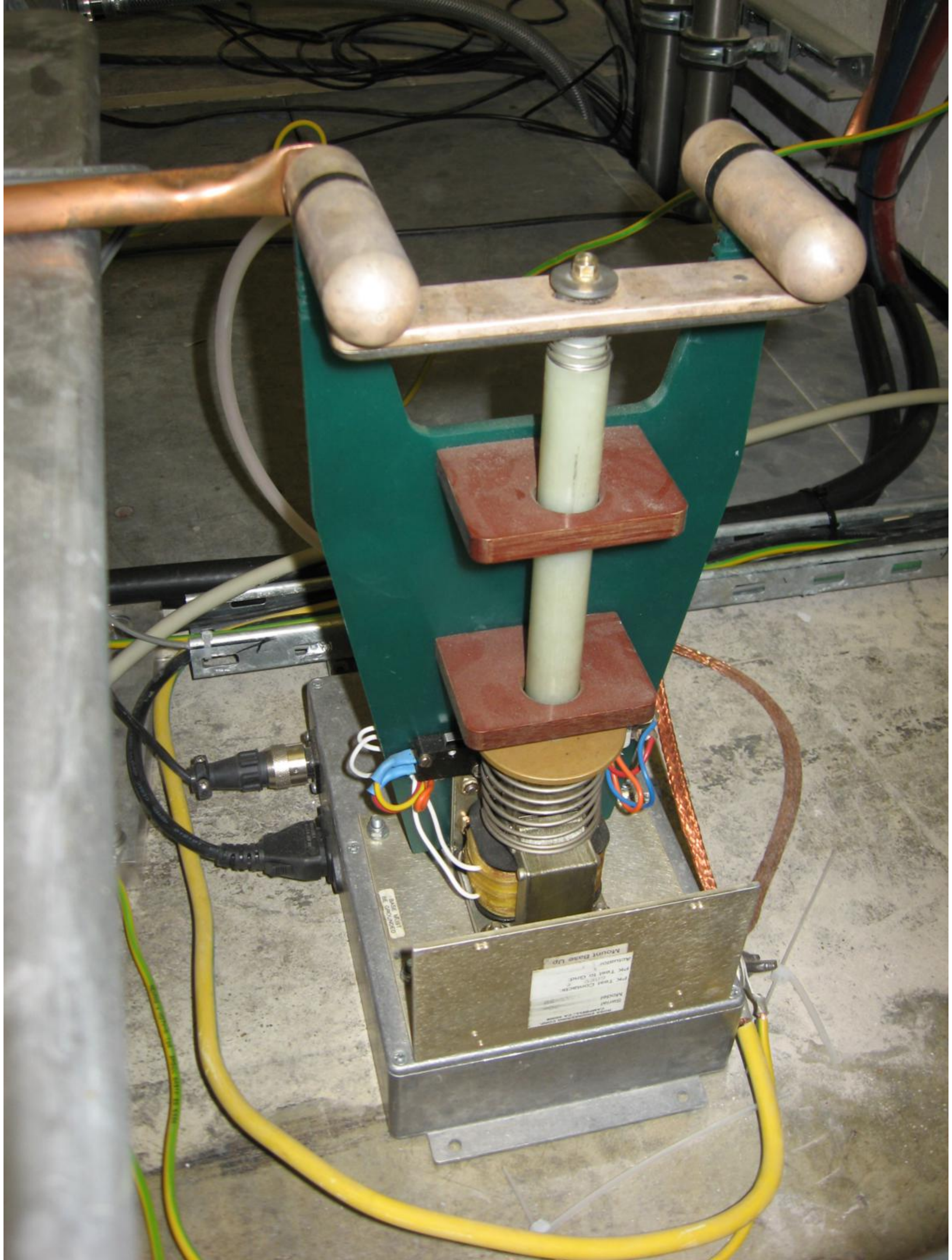
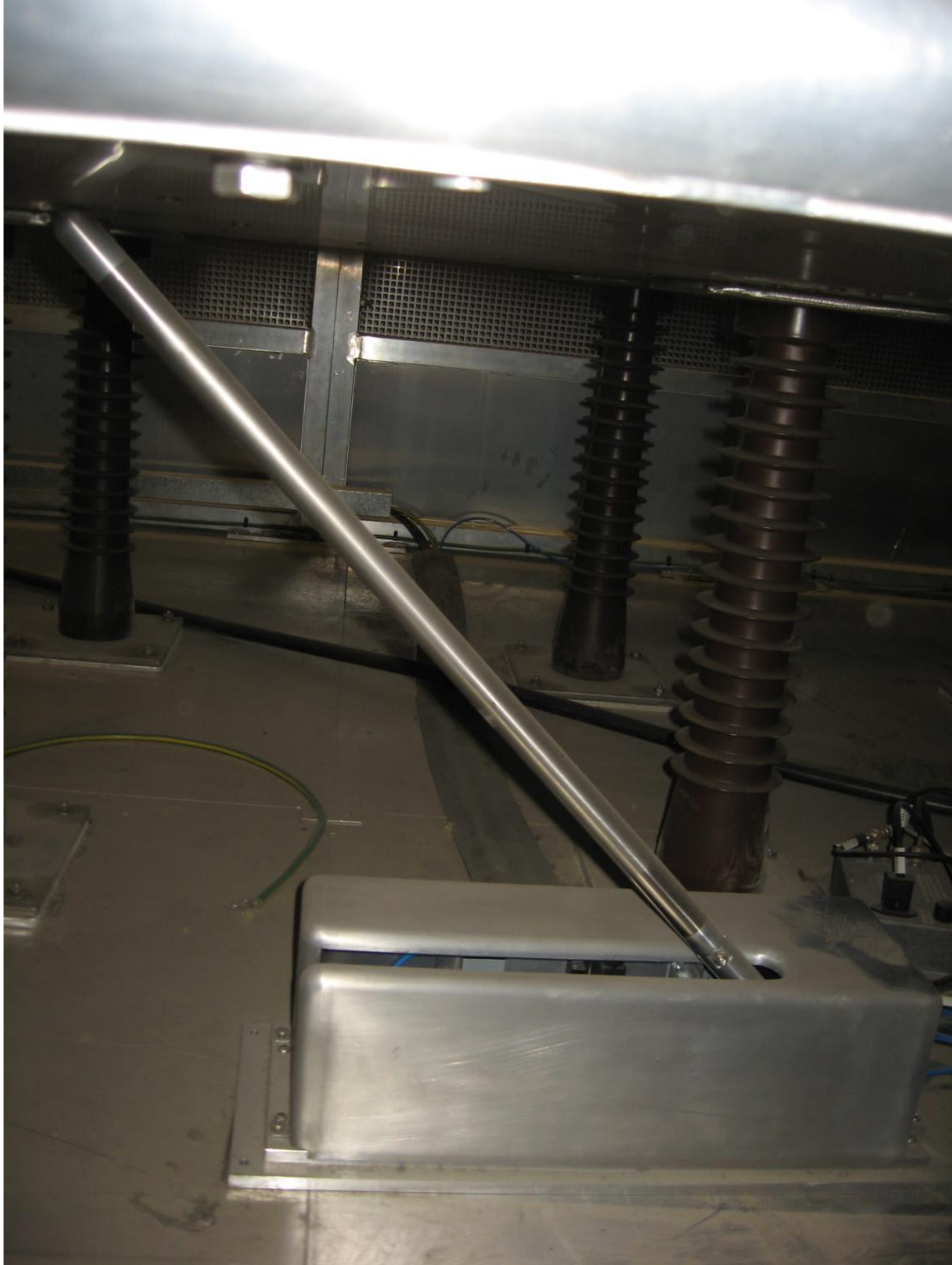
CSI

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

Example of very bad safety systems:

Cautionary tale of Dr. Jon Osterman...


INTRINSIC FIELD
LABORATORY

Let that be a lesson!

Thank you for listening