Welcome!

Cockcroft Institute Lectures – Register Attendance

CI-ACC-221: Ion Sources and Secondary Beams
Dan Faircloth (DF) RAL/STFC

CI-RF-222: RF Linear Accelerators
Graeme Burt (GB) CI/Lancaster University

CI-ACC-225: Electron Sources
Boris Militsyn (BM) CI/ASTeC

CI-ACC-226: Machine Learning Methods for Particle Accelerators
Andrea Santamaria Garcia (ASG) CI/University of Liverpool

Date/time	10:30	11:45	14.00
9 Feb 2026	Ion Sources		Penning Magnetron
16 Feb 2026	High Voltage		Secondary Beams

QR code will take you to a Google form

Record attendance for each day of lectures

Technological Aspects: High Voltage

Dan Faircloth
ISIS Low Energy Beams Group Leader
Rutherford Appleton Laboratory
STFC-UKRI

CI Lectures 2026 Daresbury

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

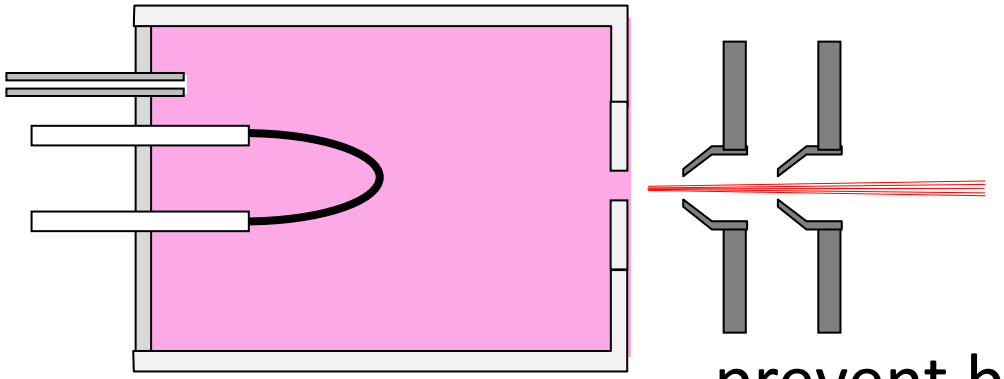
X-rays

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

This may instantaneously cause permanent damage,

or damage might slowly occur,

or the system may come to no harm.

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:

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

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

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

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

or

Poisson's Equation

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

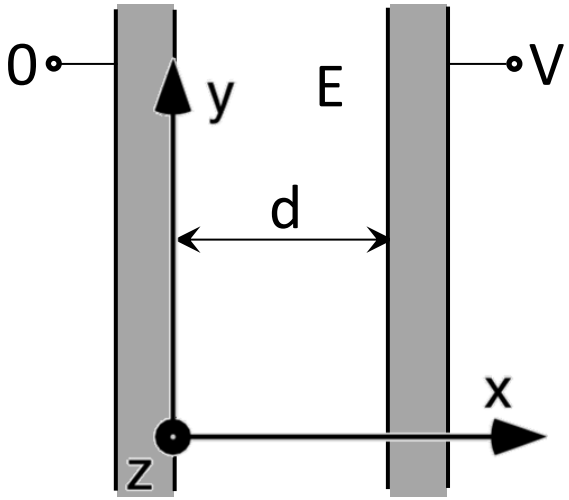
if $\rho = 0$:

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

Infinite parallel plates:



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

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

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

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

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

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

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

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

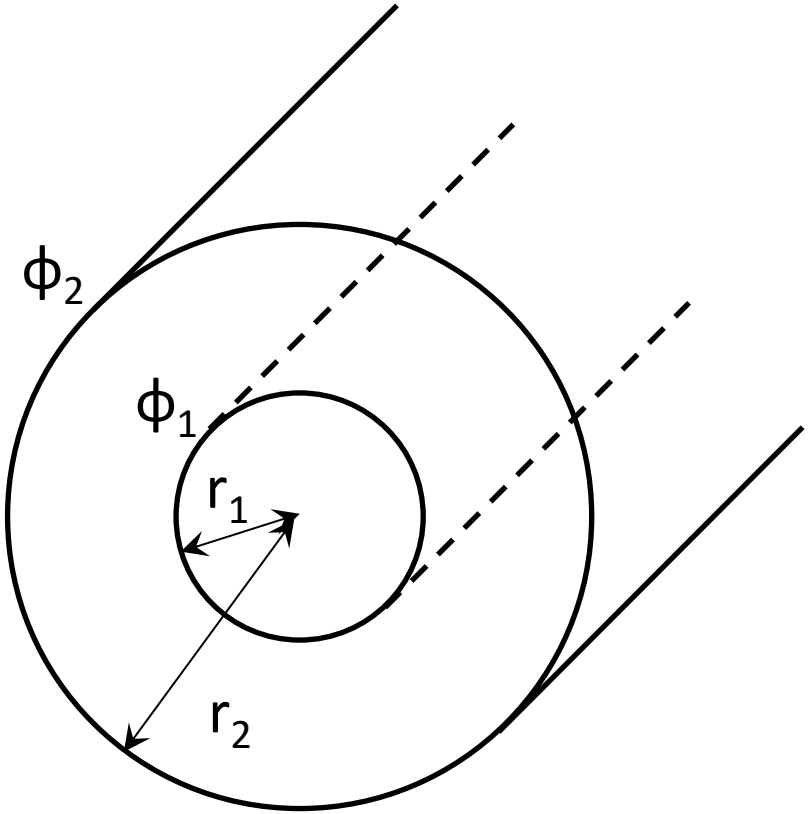
At $x = 0,\ \phi = 0$ and at $x = d, \phi = V$

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

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

Similarly....

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



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

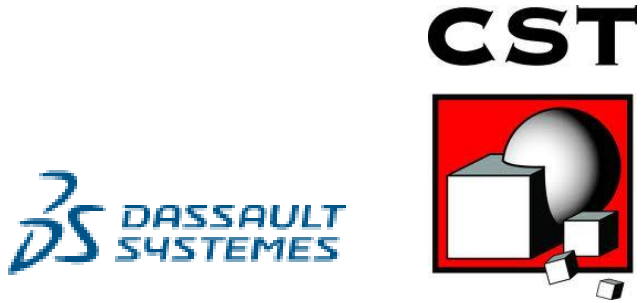
$$E(r)=\frac{\phi_1-\phi_2}{r\ln\left(\frac{r_2}{r_1}\right)}$$

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

Fine for simple geometries...

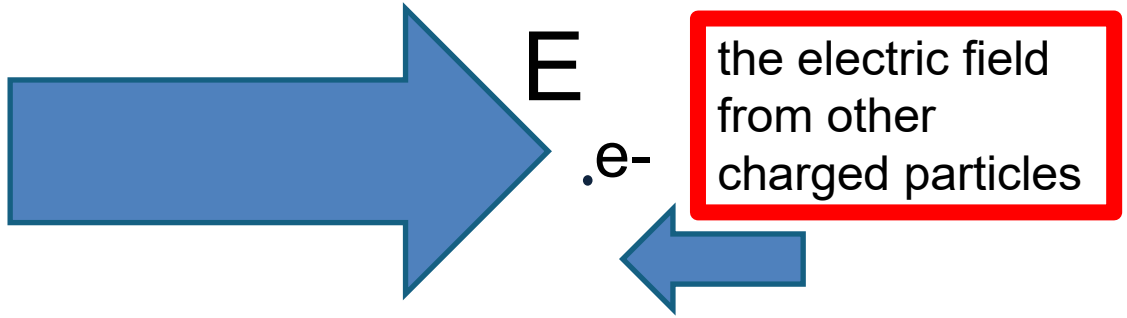
thankfully we have computers

3D Modelling Software- Commercial and Open Source



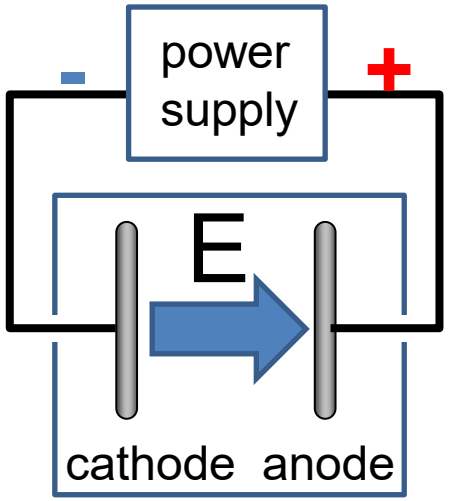
Plus many others...

Accelerating electrons



Capacitively Coupled Plasmas (CCP)

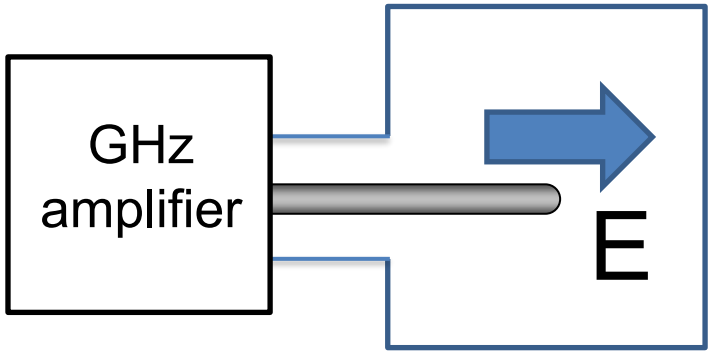
voltage applied to electrodes creates the electric field



many different electrode and magnetic field configurations
DC and AC

Electromagnetic Cavity Plasmas - waveguide or coax coupled

the electric field component of the electromagnetic oscillation in a cavity

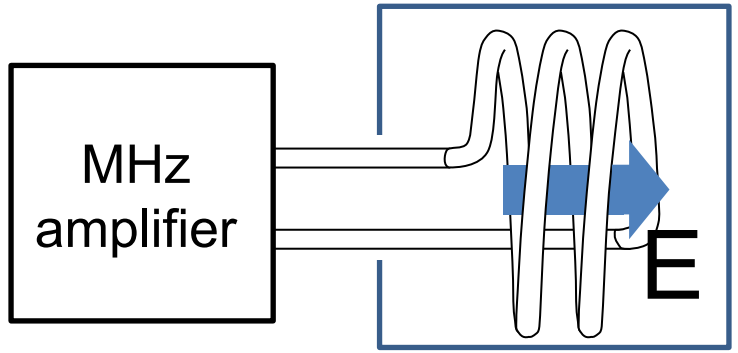


"Microwave sources"
"ECR sources"

Inductively Coupled Plasmas (ICP)

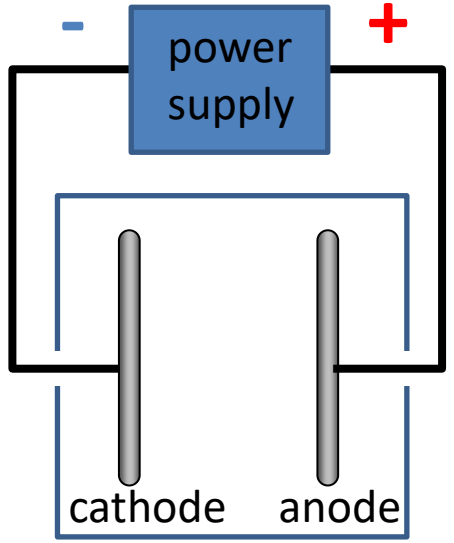
a time varying current in a coil creates a time varying magnetic field that induces a time varying electric field

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$

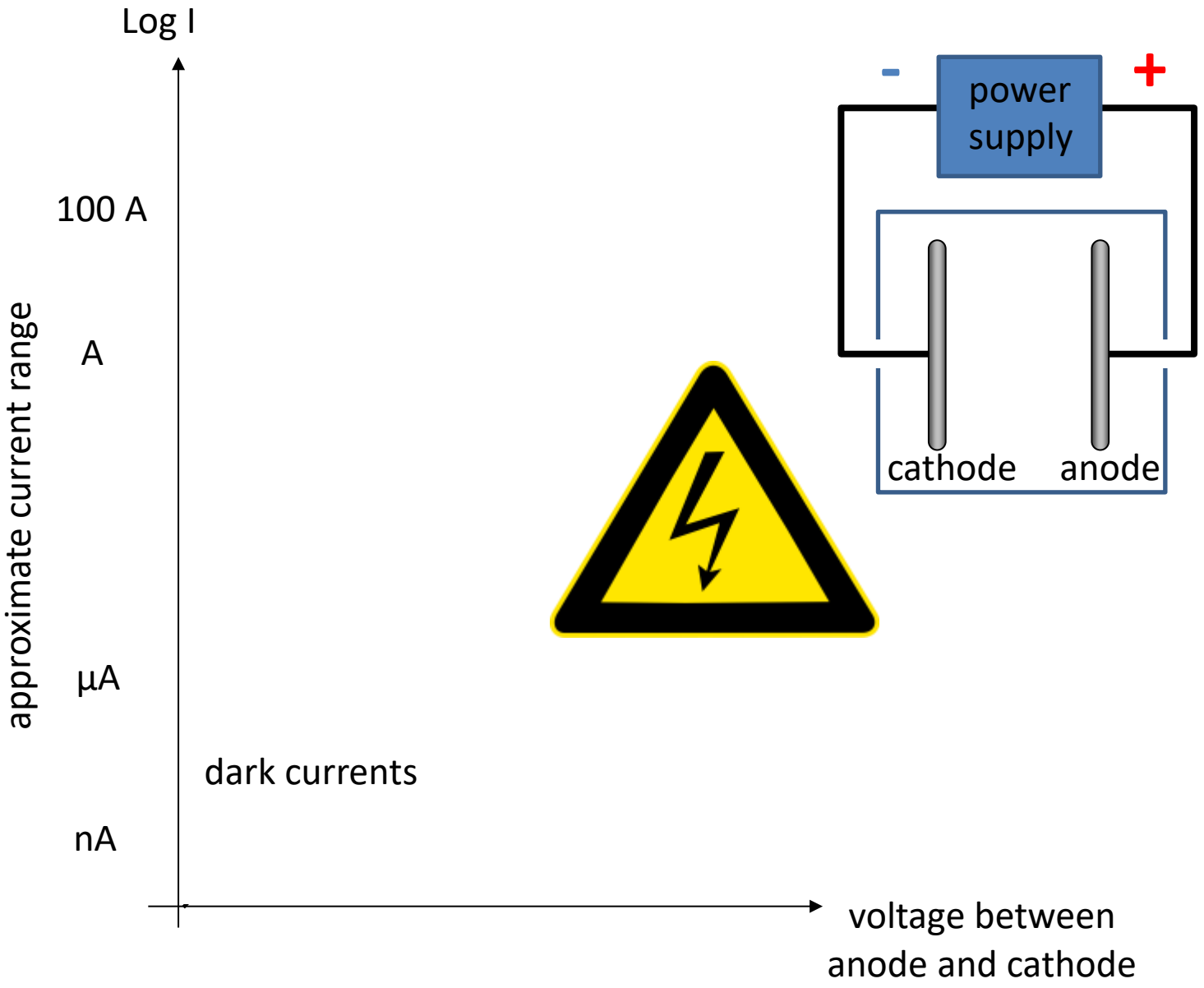


"RF sources"

Electrical Discharges



Electrical Discharges



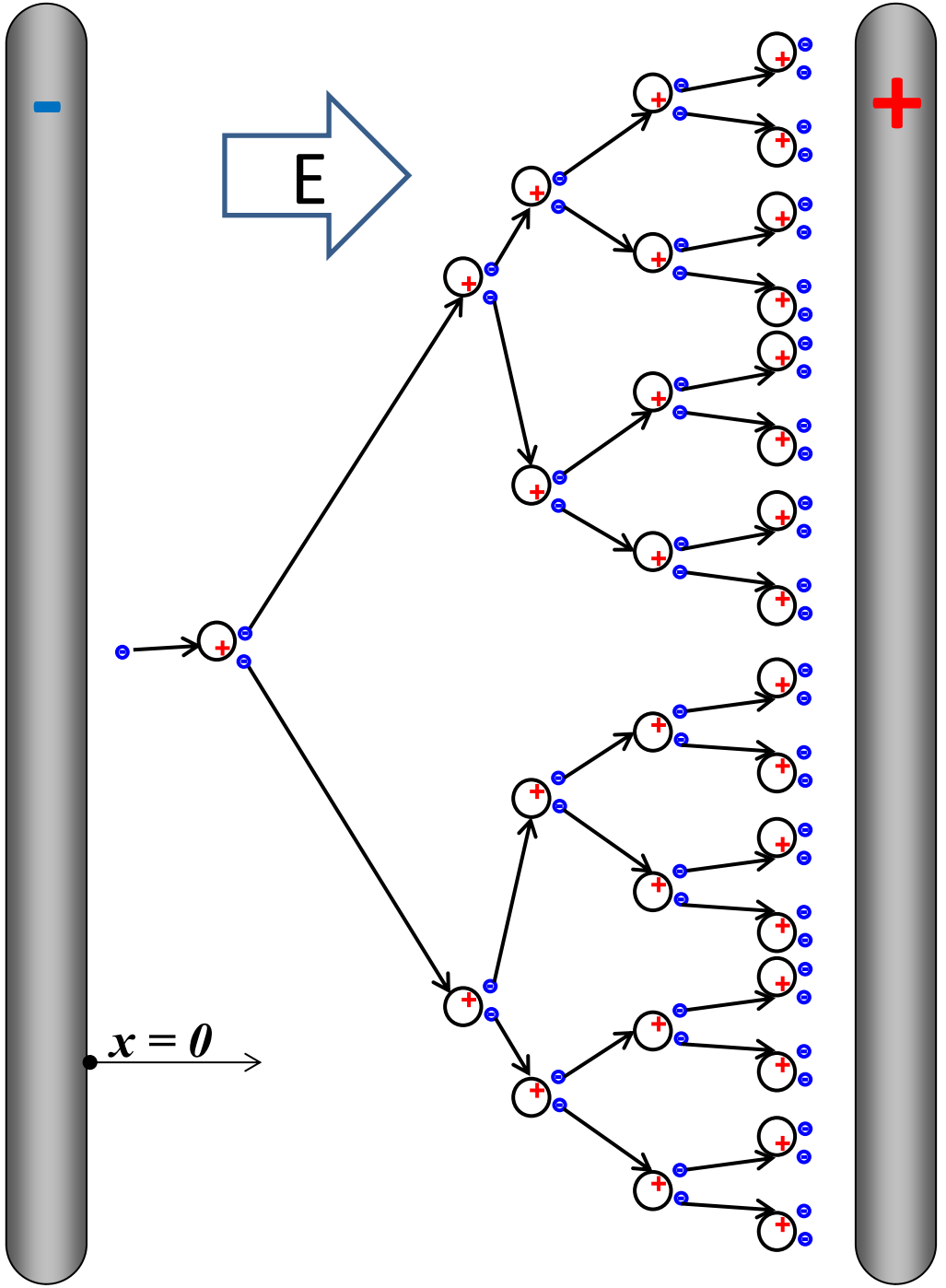
Avalanche

John Townsend
"Townsend discharge"
1897

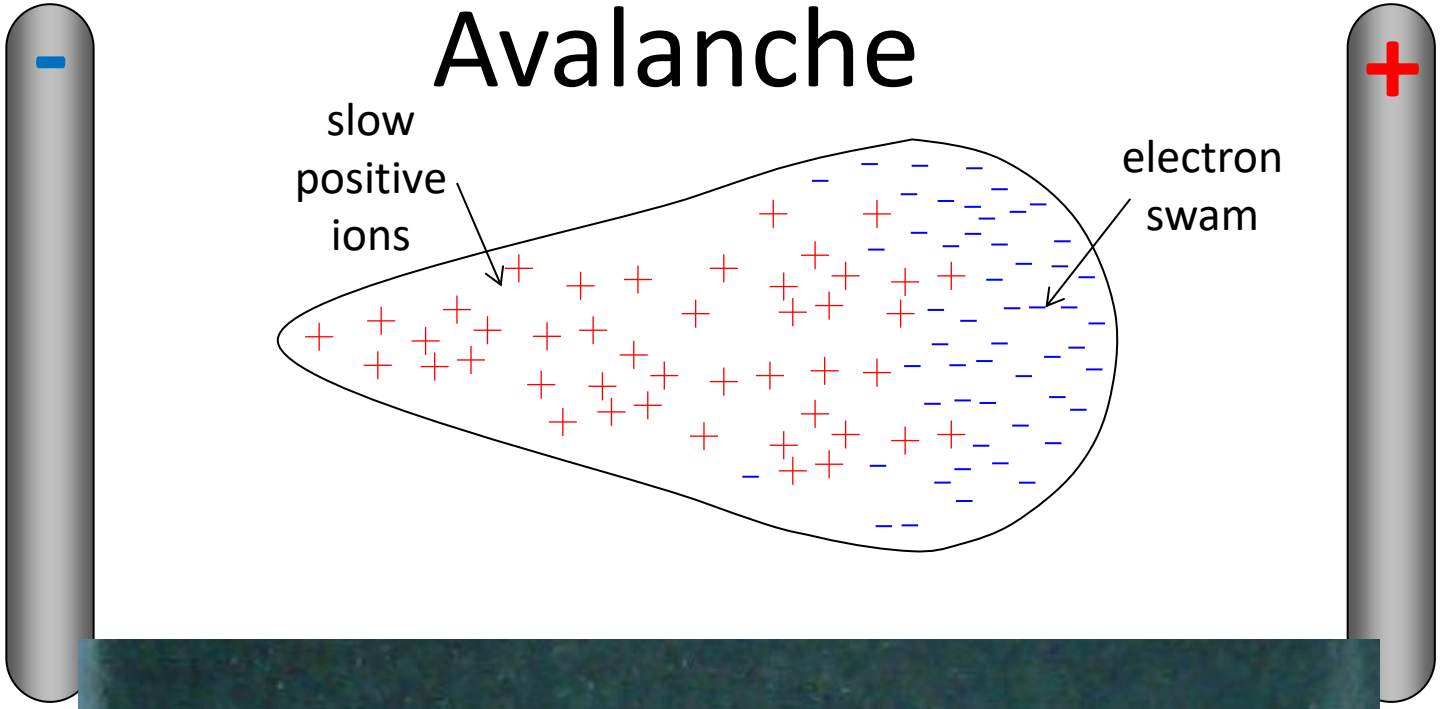
$$dn_x = n_x \alpha dx$$

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

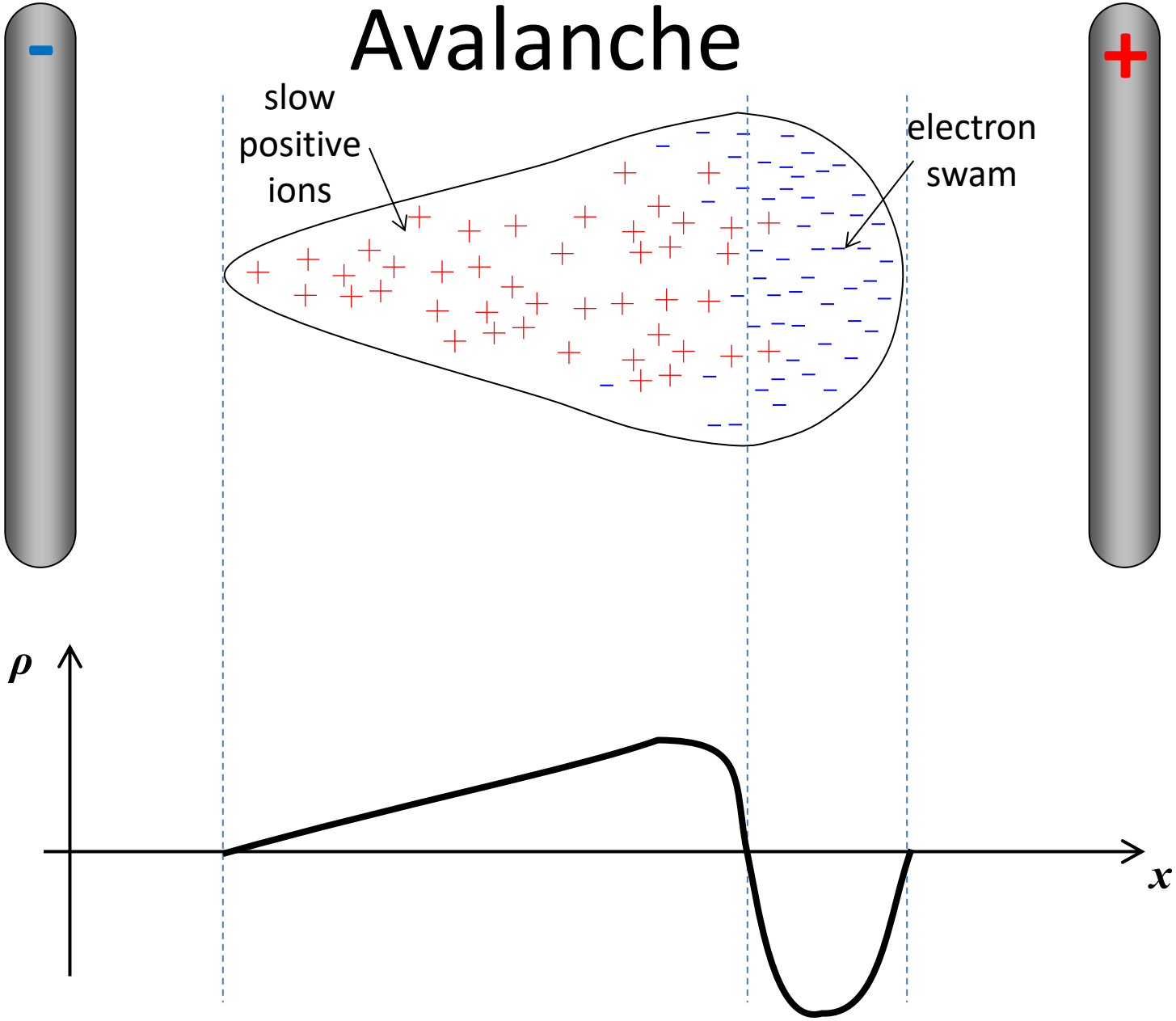
$$n_x = n_0 e^{\alpha x}$$



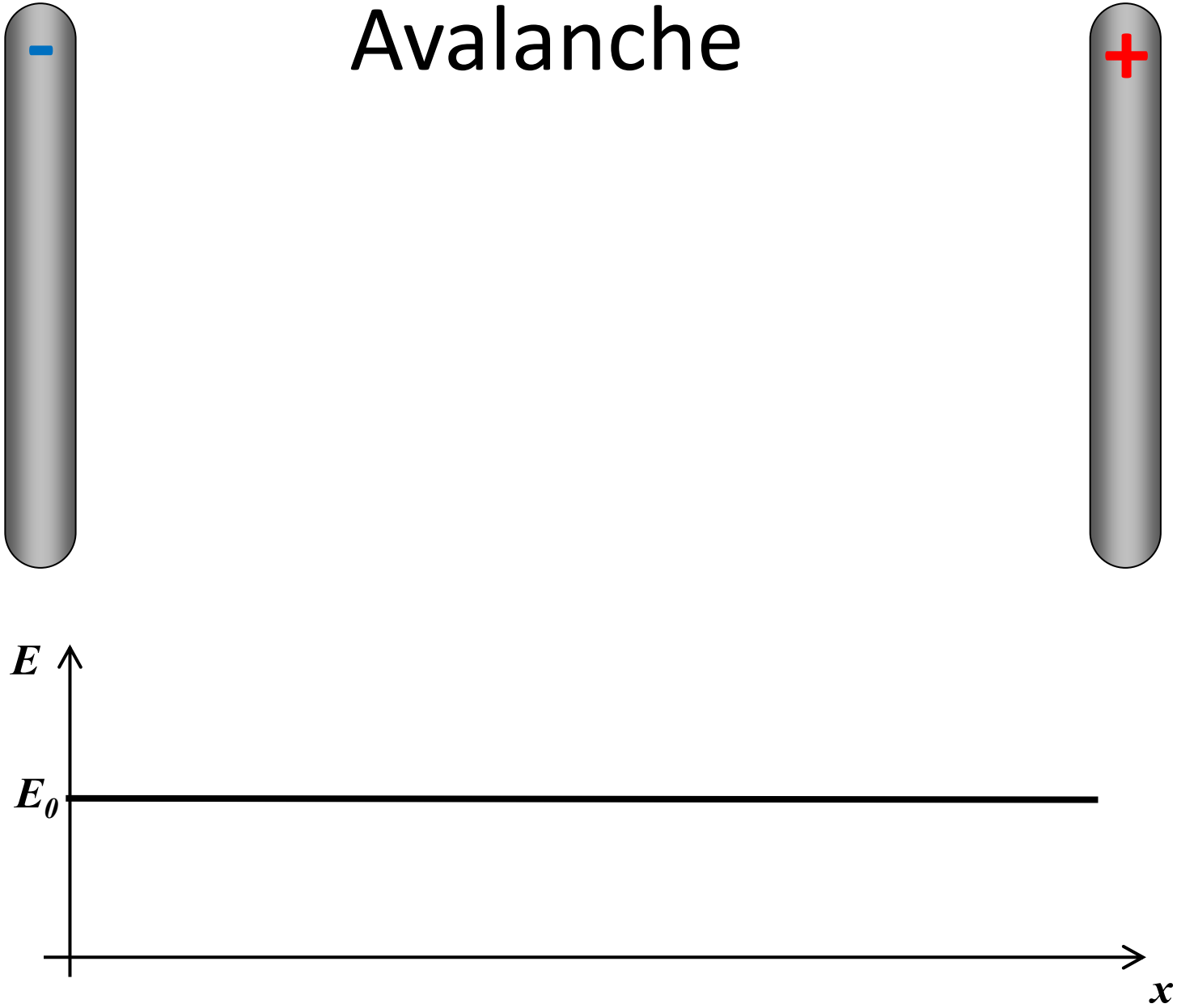
Avalanche



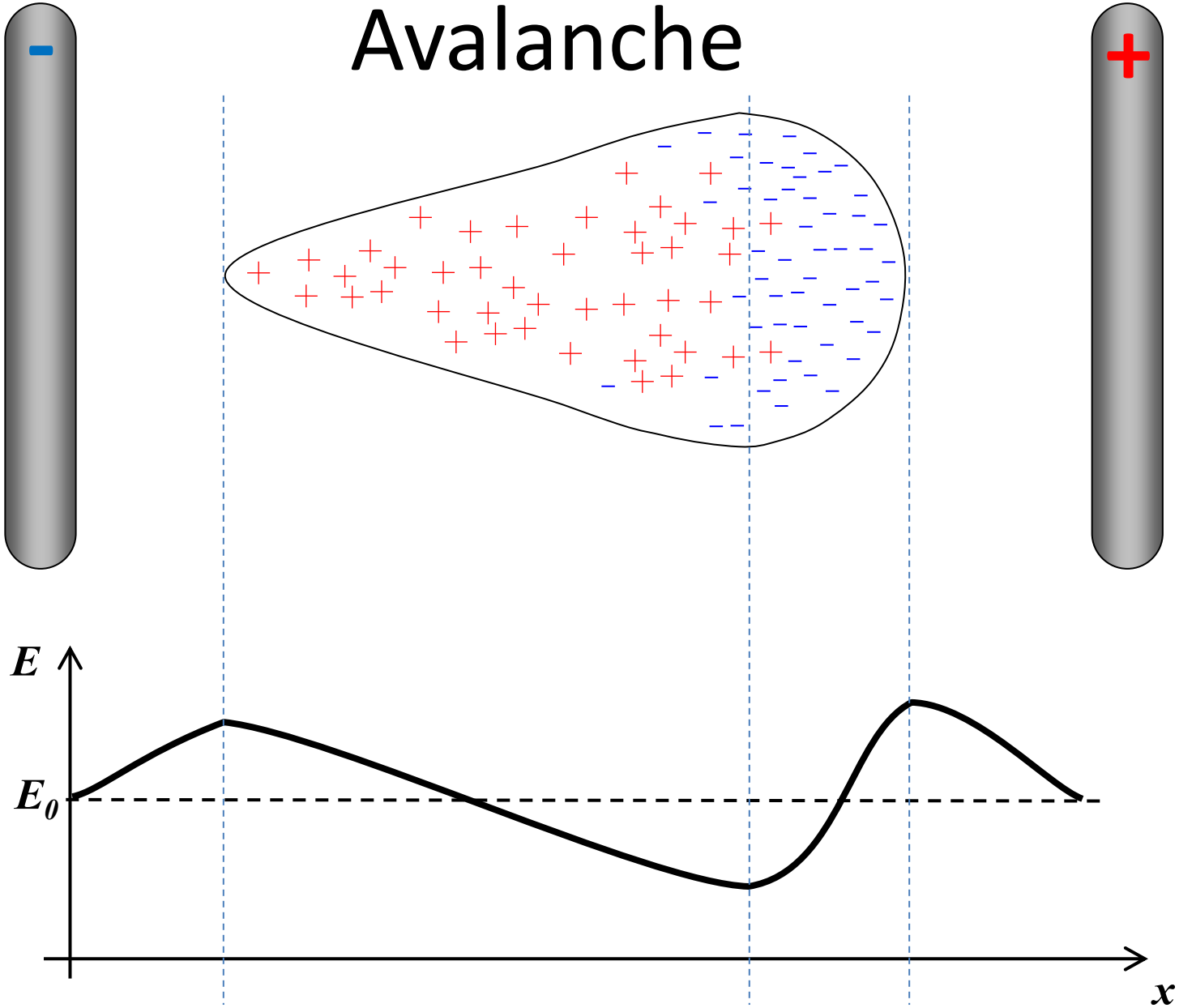
Avalanche



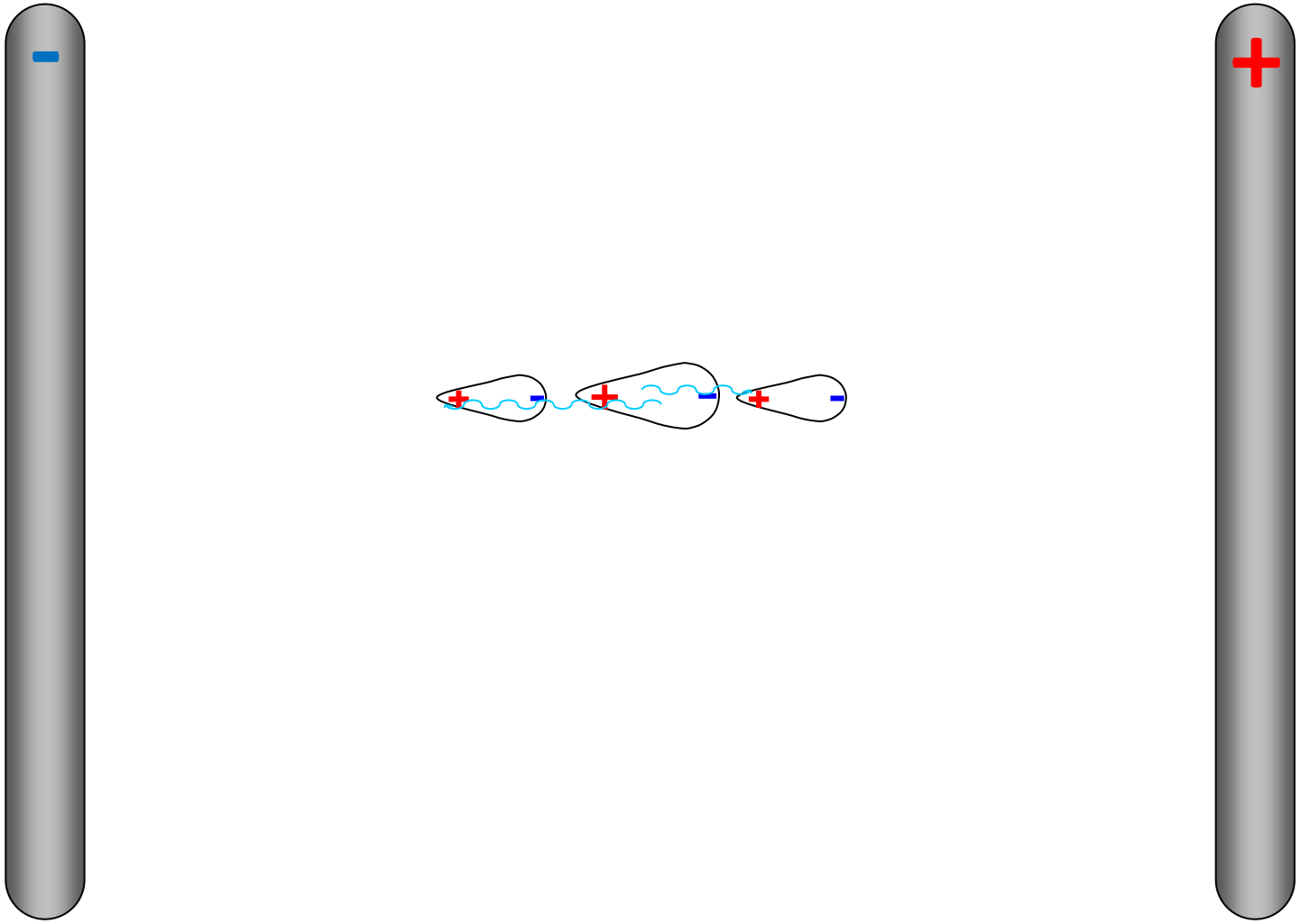
Avalanche



Avalanche



Streamer



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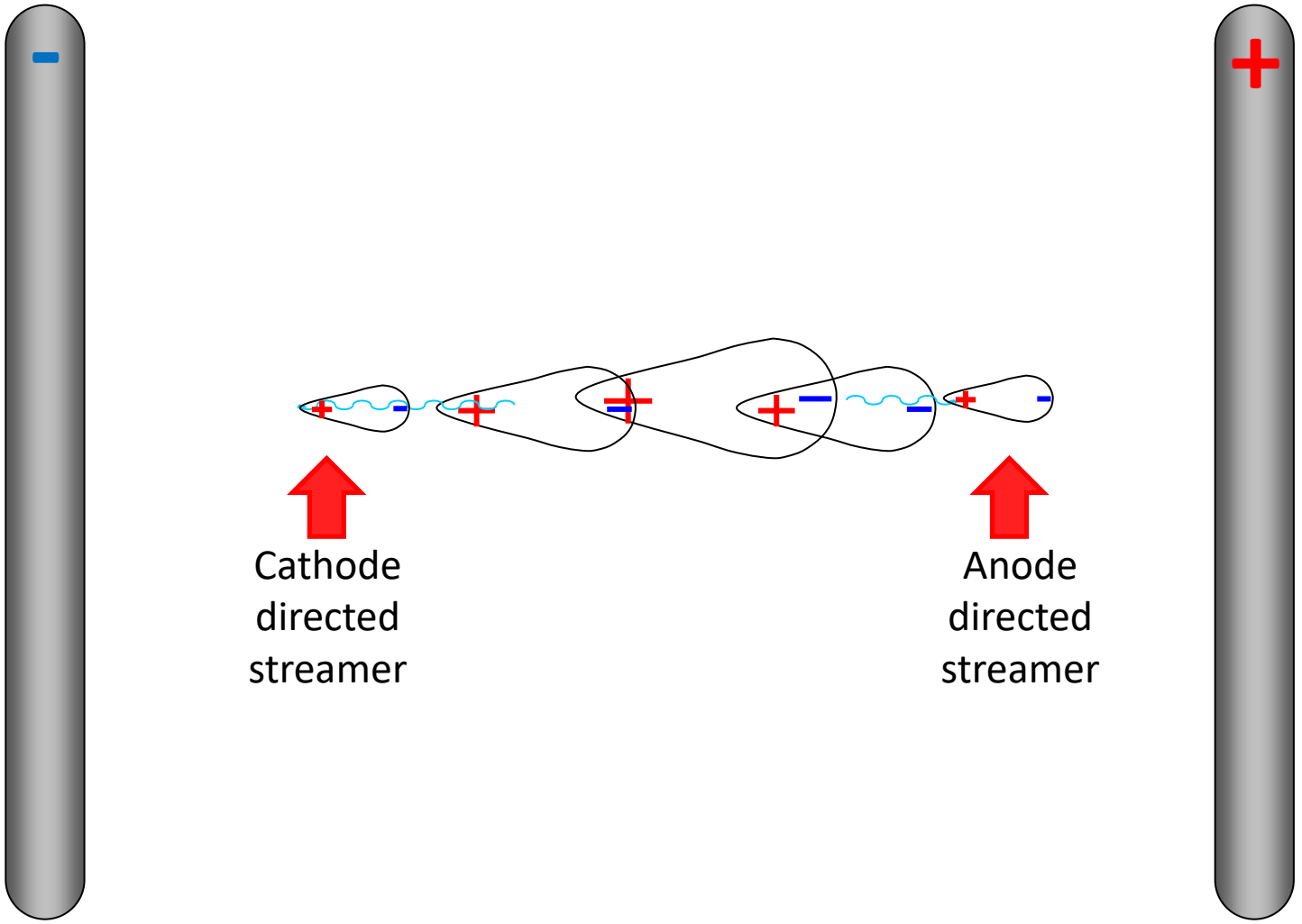

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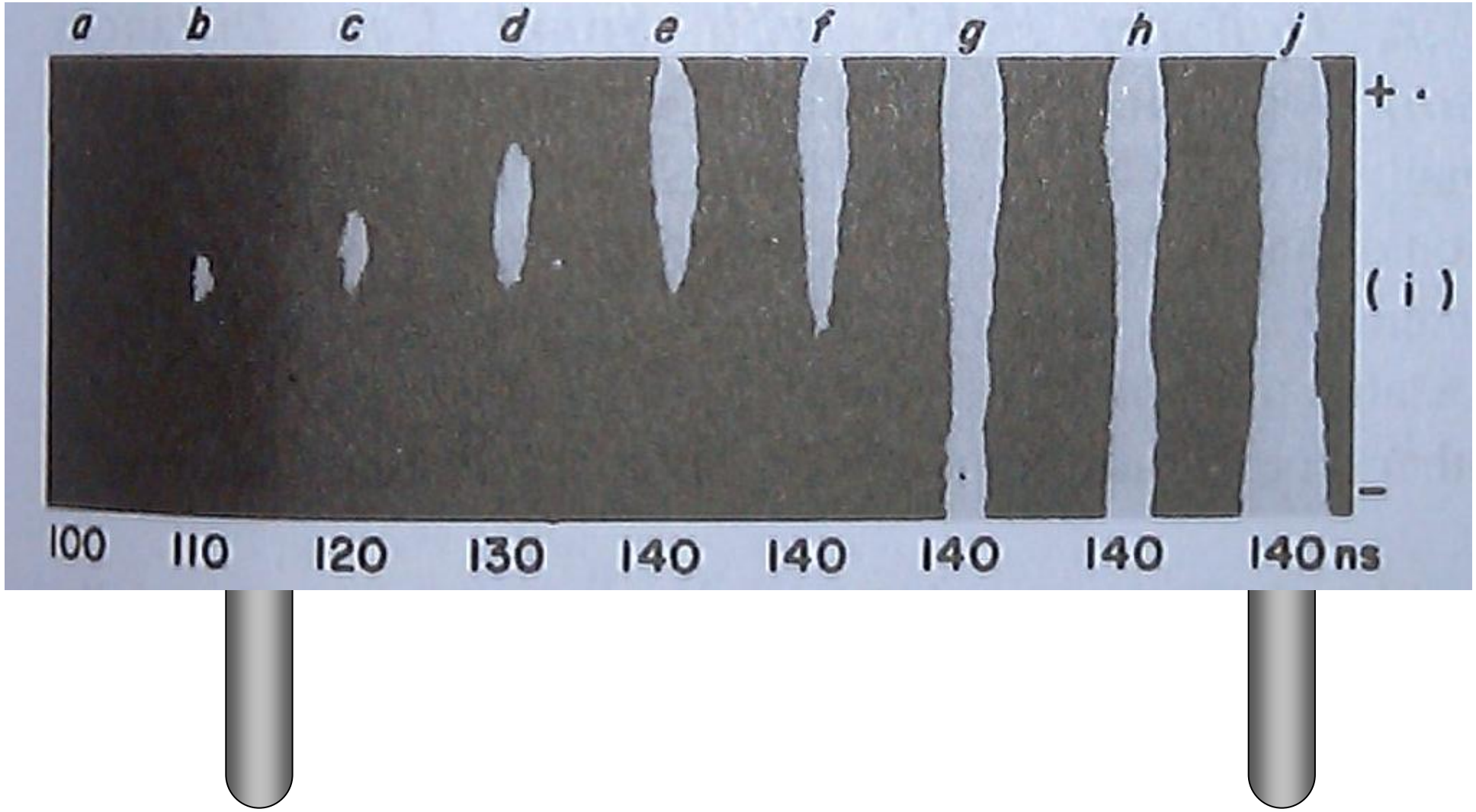


Townsend Secondary Ionisation Coefficient, γ

John Townsend
"Townsend discharge"
1897

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

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

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

$$dn_x = n_x \alpha dx$$

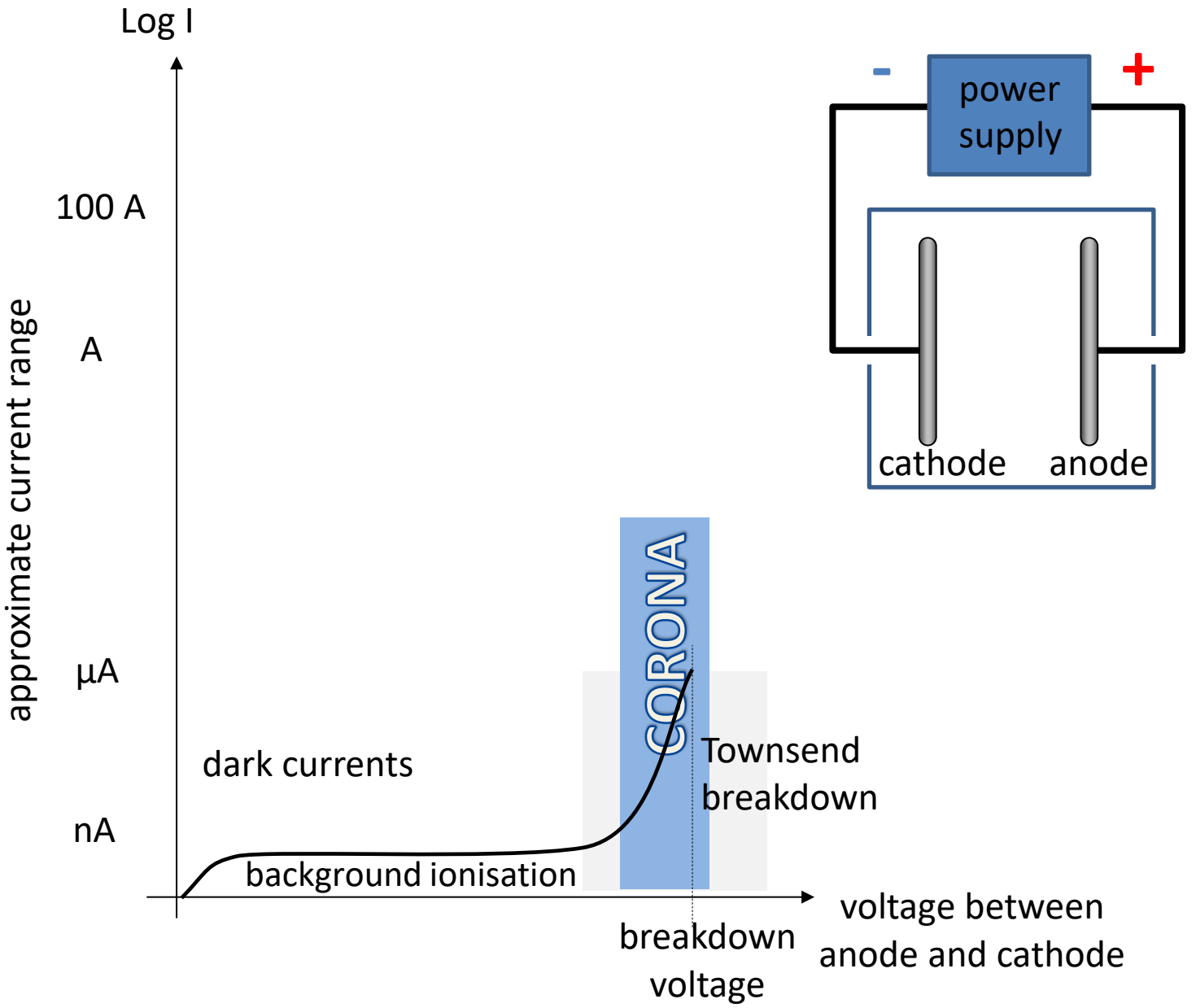
$$n_x = n_0 e^{\alpha x}$$

Self sustaining discharge resulting in breakdown when:

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

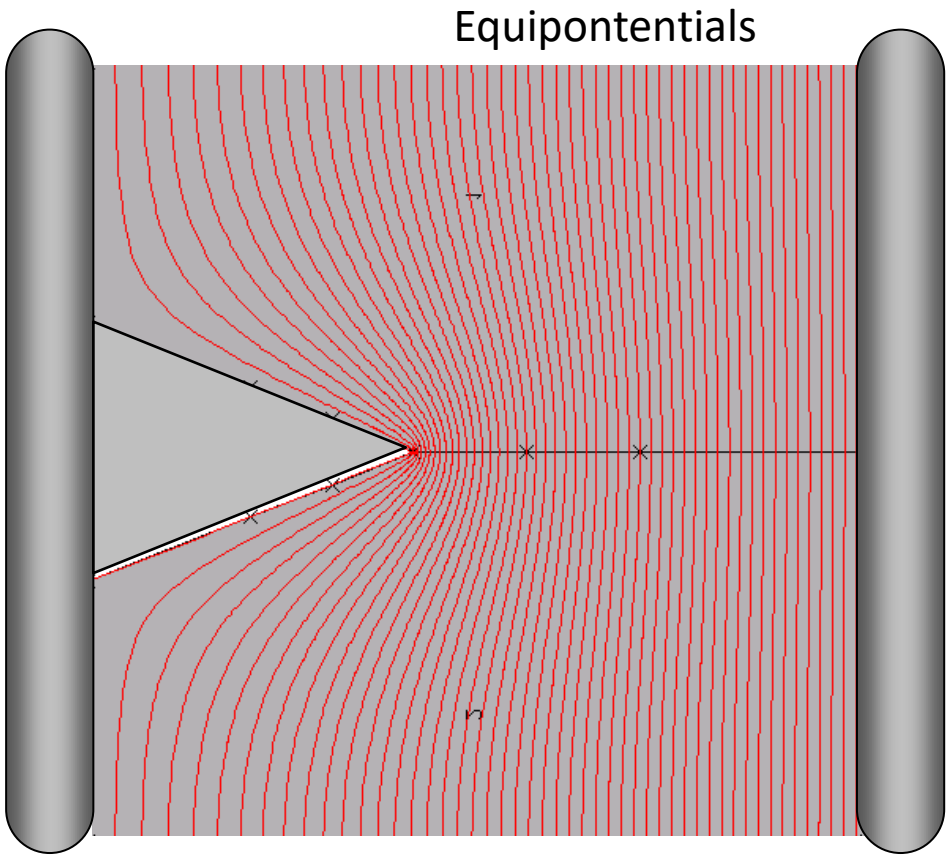
Townsend Criterion for Breakdown

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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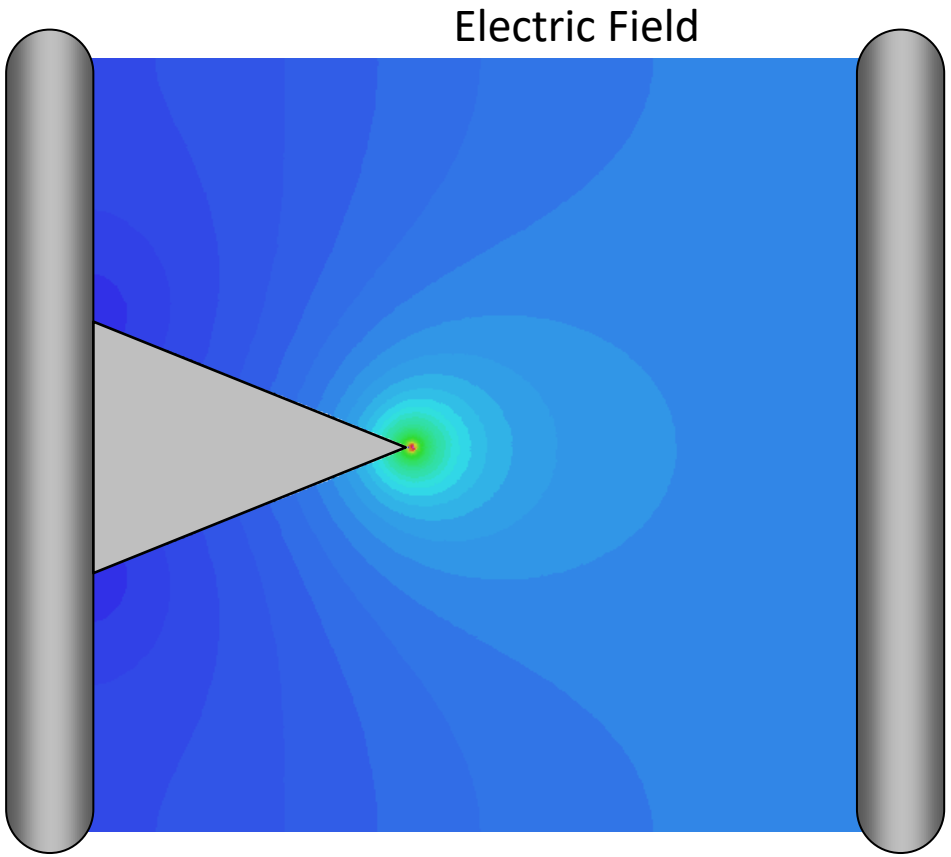
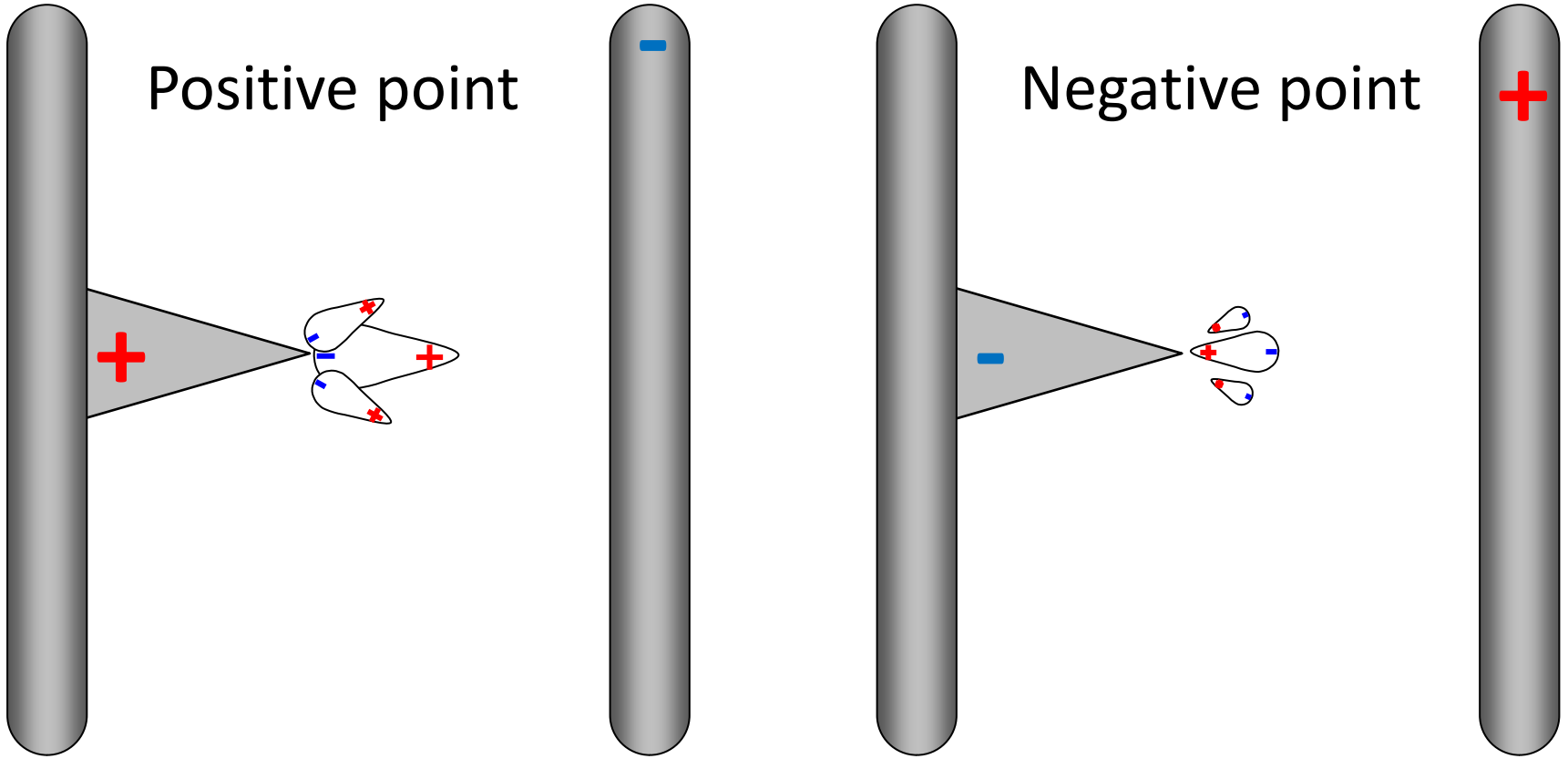


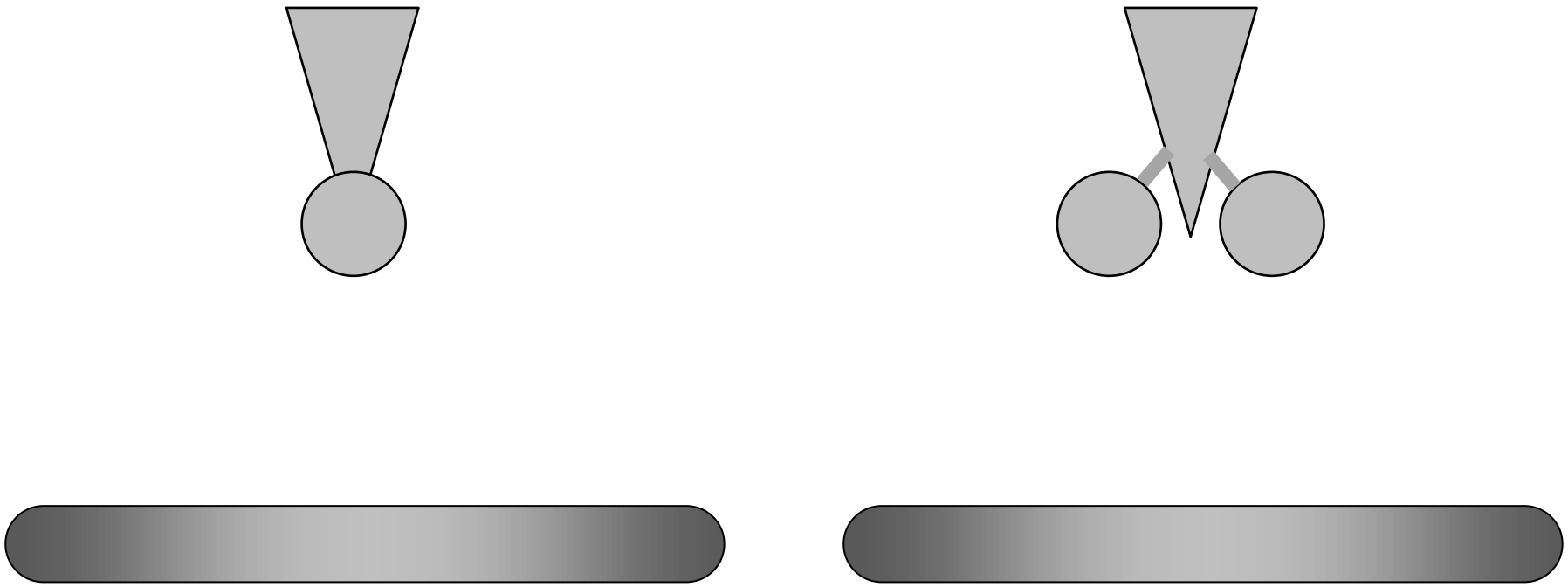
Corona

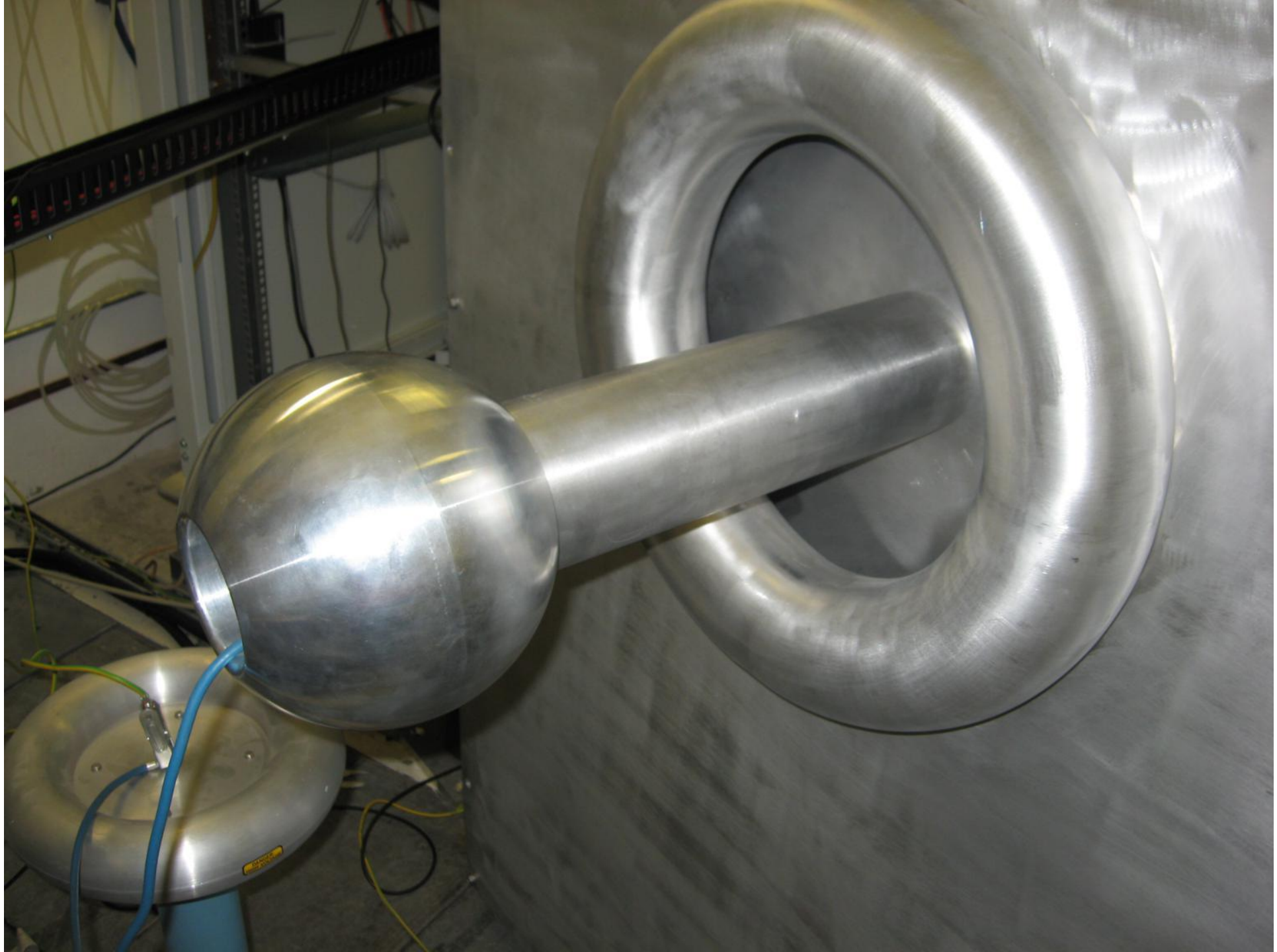
- Corona is a type of partial discharge occurring in divergent fields
- Divergent fields are caused by sharp points
- Discharge behaviour is dependant on polarity



Electrode Design

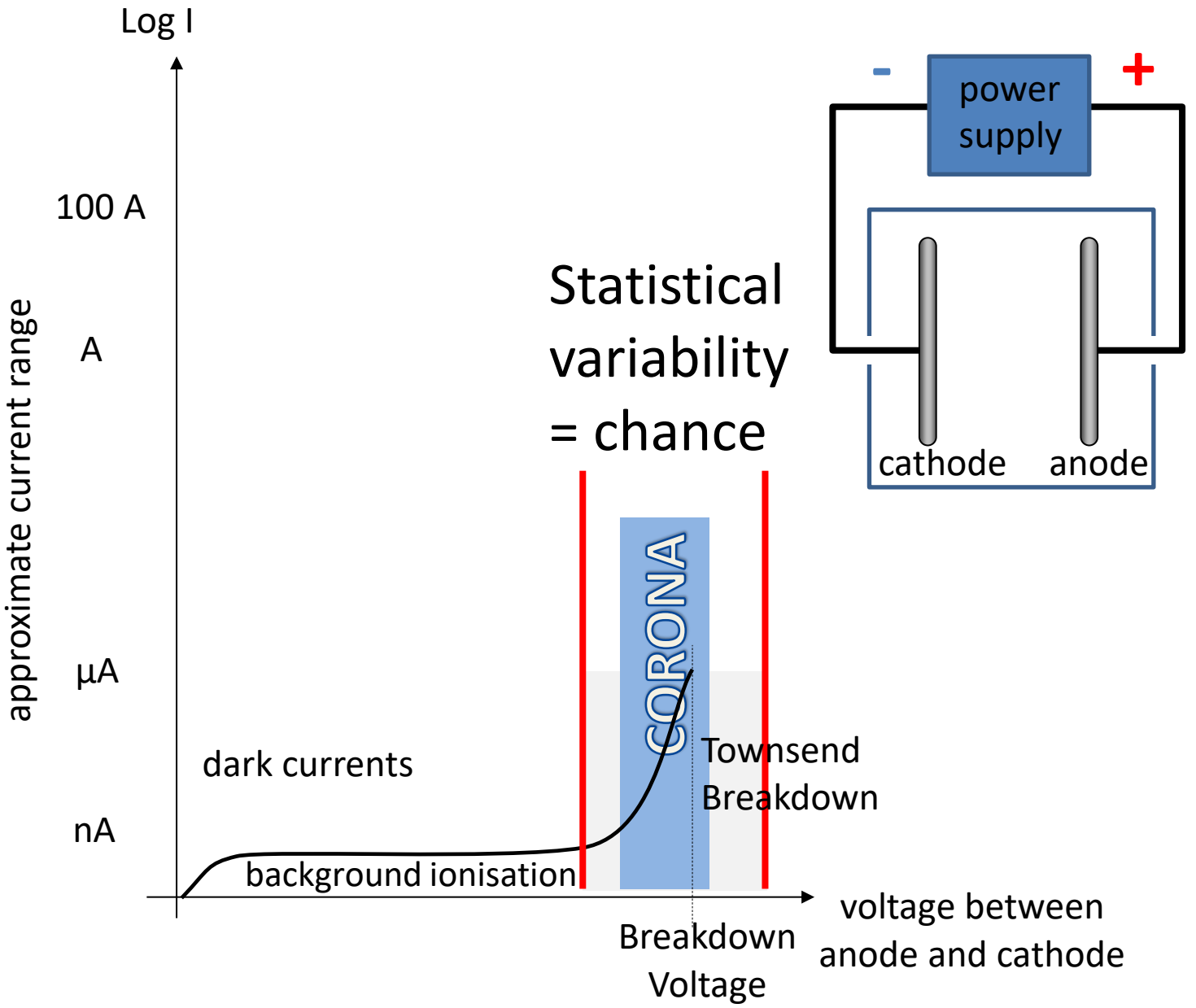
- Minimise electric field by making smooth rounded electrodes
- Shield any sharp points with corona shields





JLG LIFT

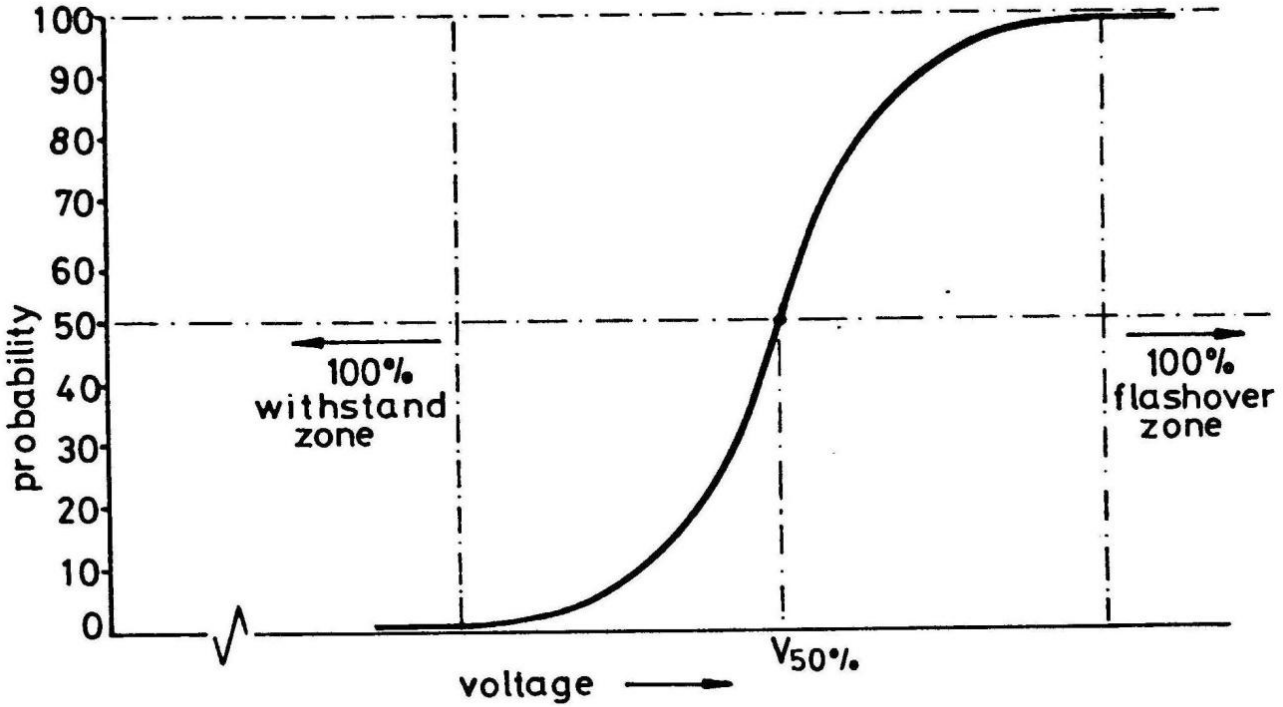
Electrical Discharges

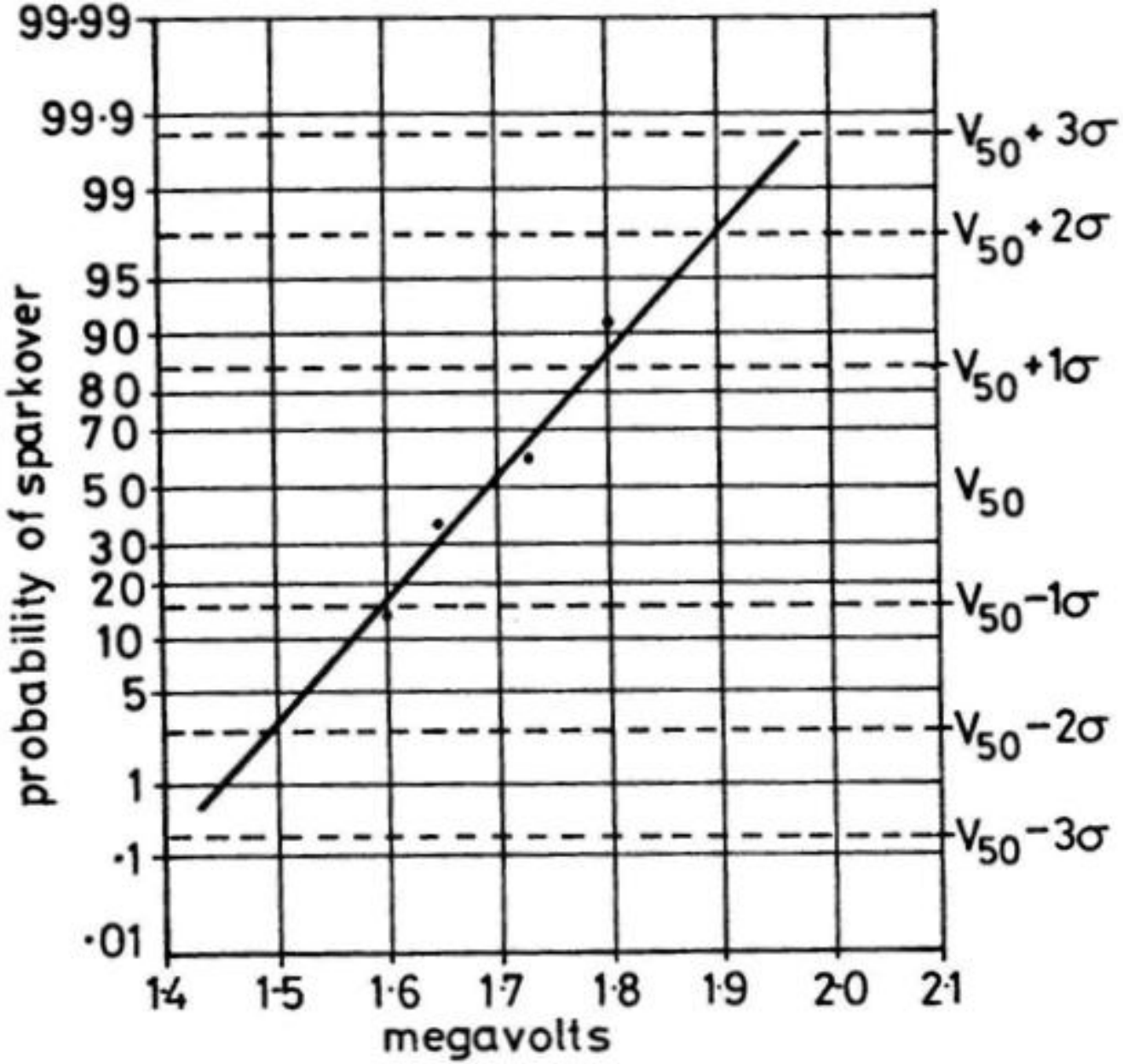


Statistical Variability

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
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

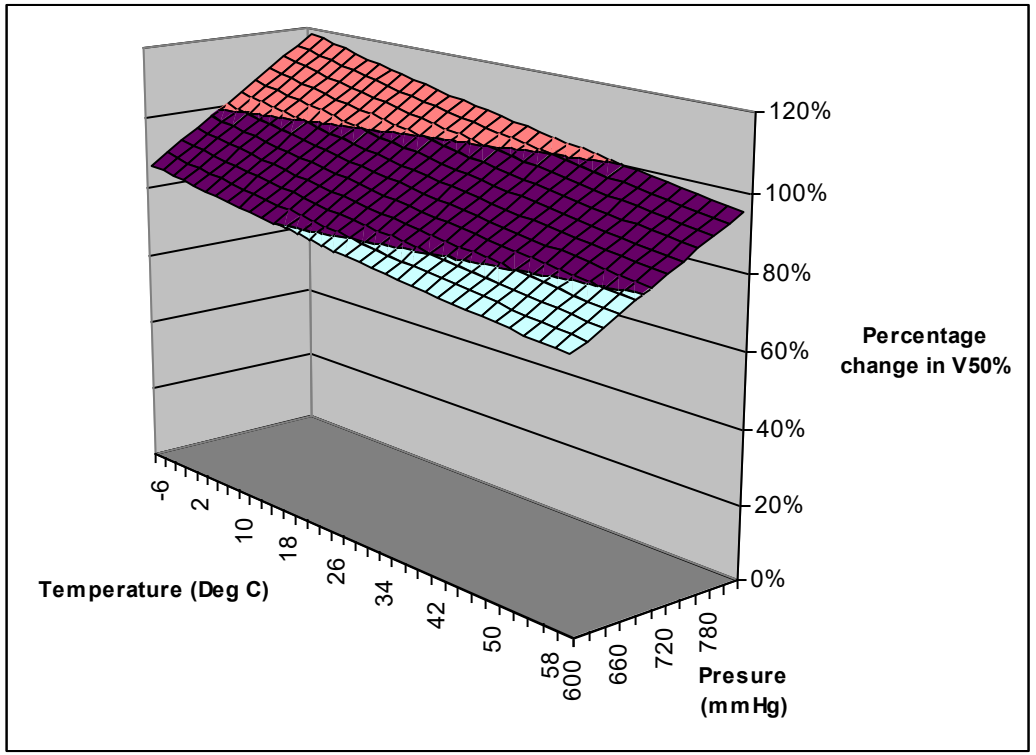
Higher temperatures and lower pressures lead to lower flashover voltages.

A correction factor for V50% can be found from this equation:

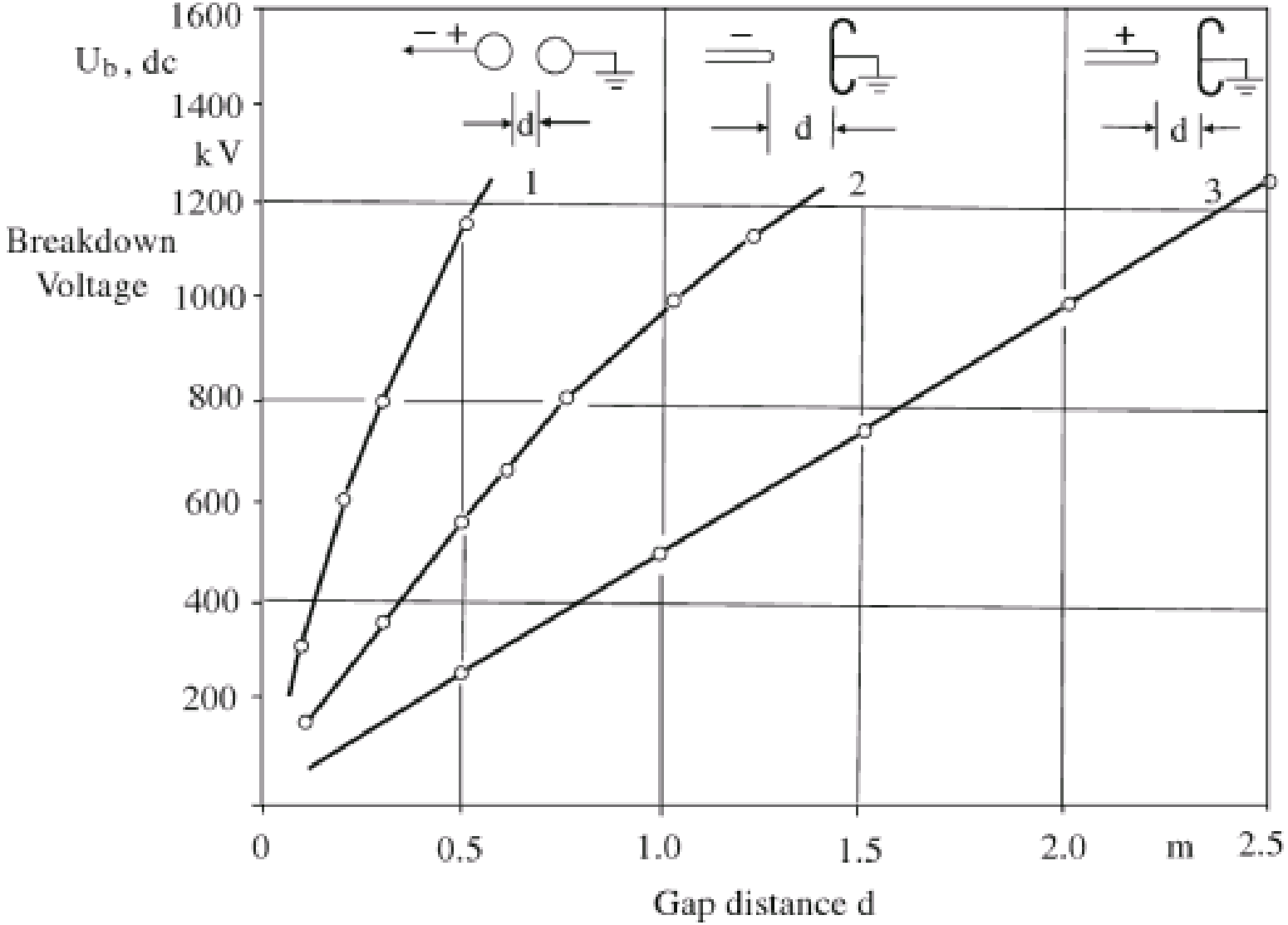
$$\frac{0.386 \times P}{273 + t}$$

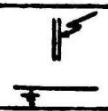
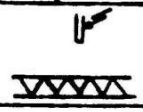
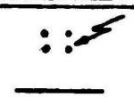
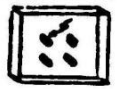
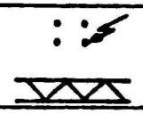
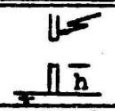
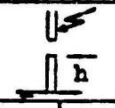
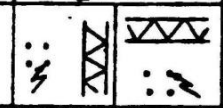
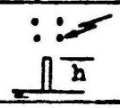
where P is in mmHg and t is in degrees centigrade.

Humidity can also affect breakdown voltage

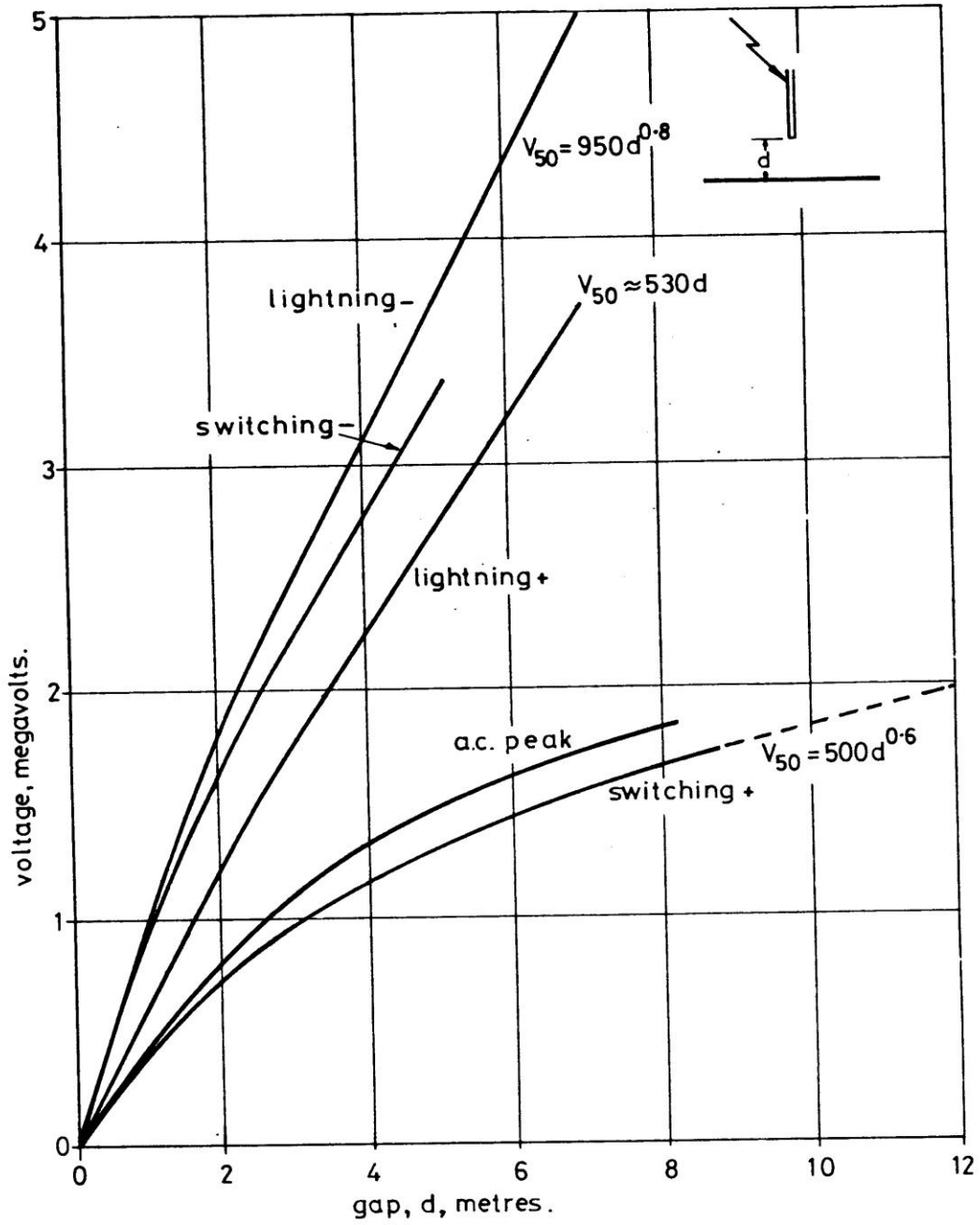


Polarity is very important in non-uniform asymmetrical gaps



	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

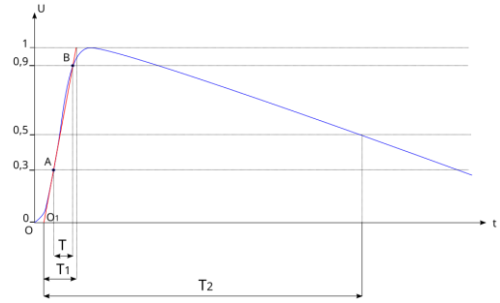
“Rule of thumb” breakdown voltage scaling factors (K) for different asymmetrical gap geometries



In asymmetric gaps the type of applied voltage is important:

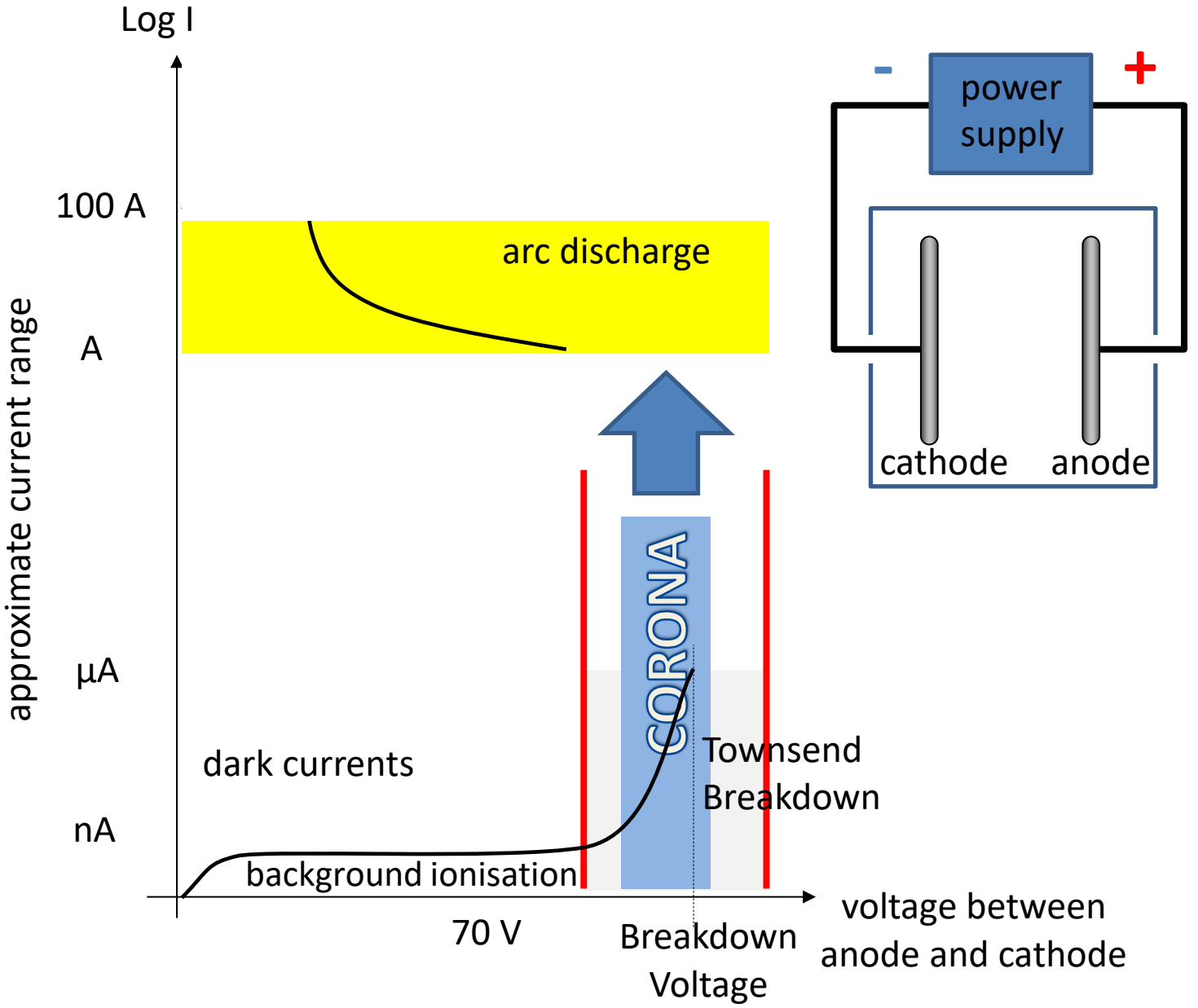
- Polarity
- DC
- AC (frequency)
- Pulsed (length)

“Standard impulses”
Lightning: 1.2/50 µs
Switching: 250/2500 µs



Electrical Discharges

Dependant on power supply and what is between electrodes



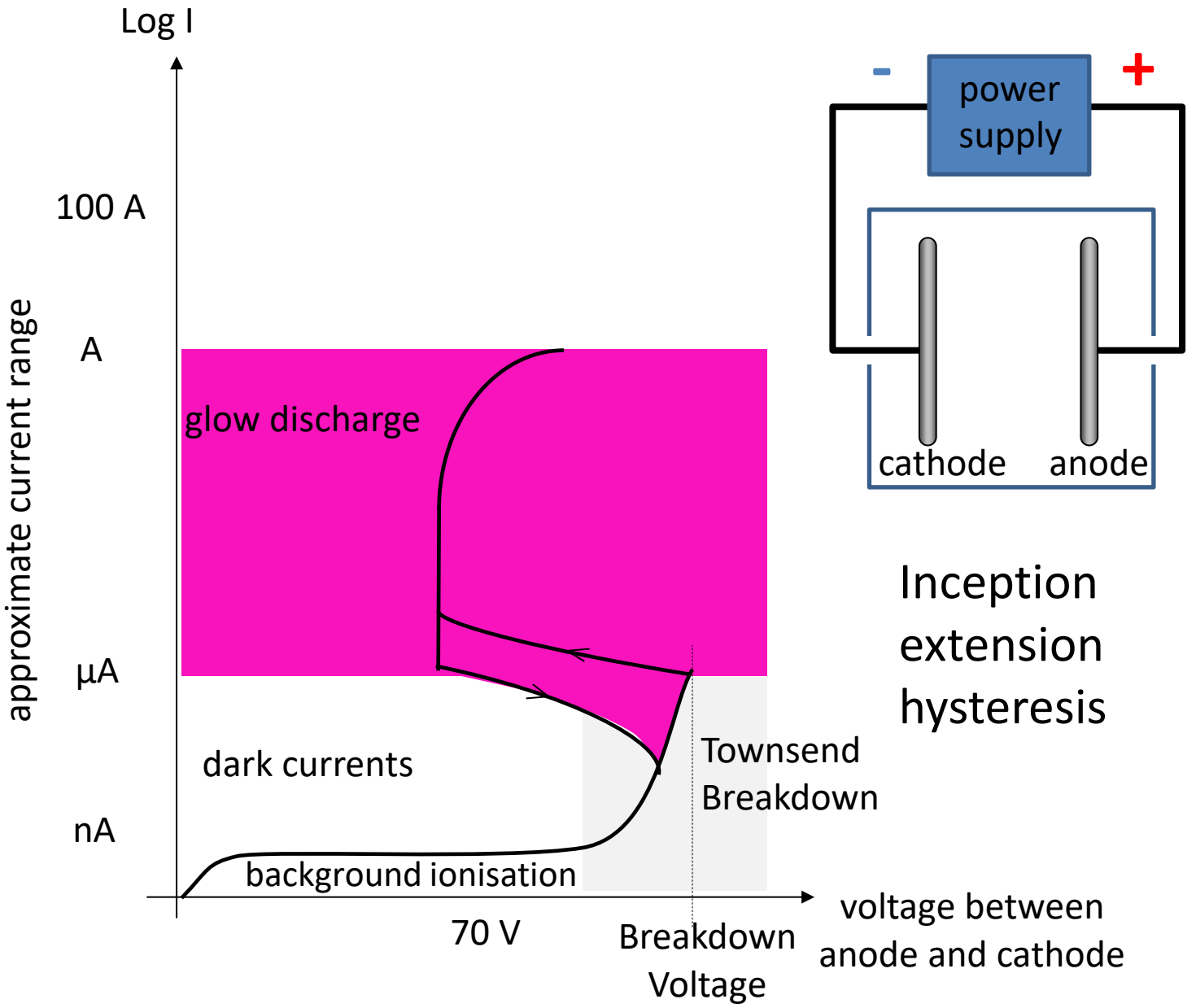
Arcs

Bad

Good

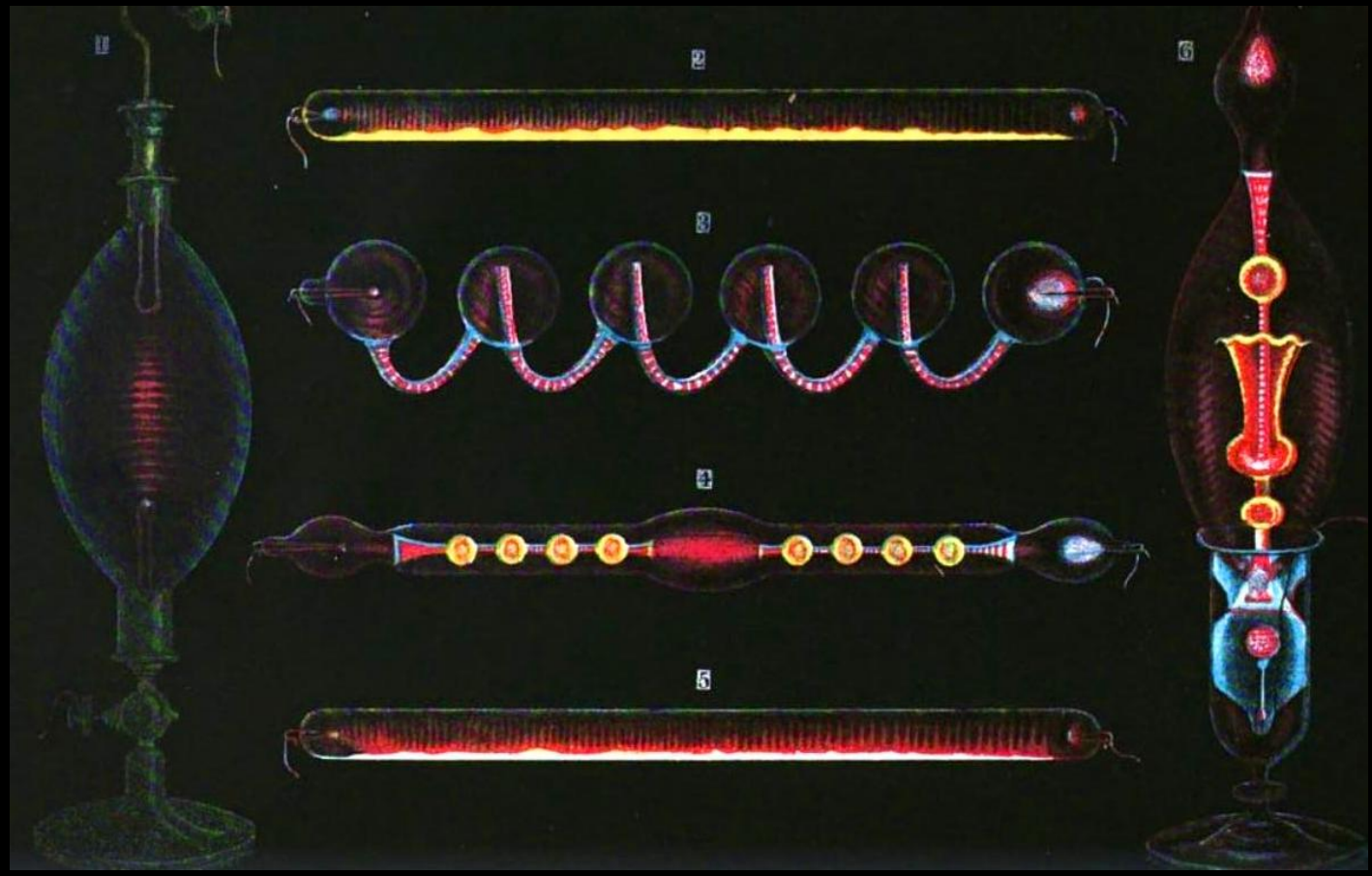
Electrical Discharges

If the pressure is low enough



Inception
extension
hysteresis

BANG
BANG



Basic Plasma Properties

Density, *n*
(per cm³ or per m³)

n_e = density of electrons

n_i = density of ions

n_n = density of neutrals

Charge State, *q*

$H^+ \rightarrow q = +1$

$Pb^{3+} \rightarrow q = +3$

$H^- \rightarrow q = -1$

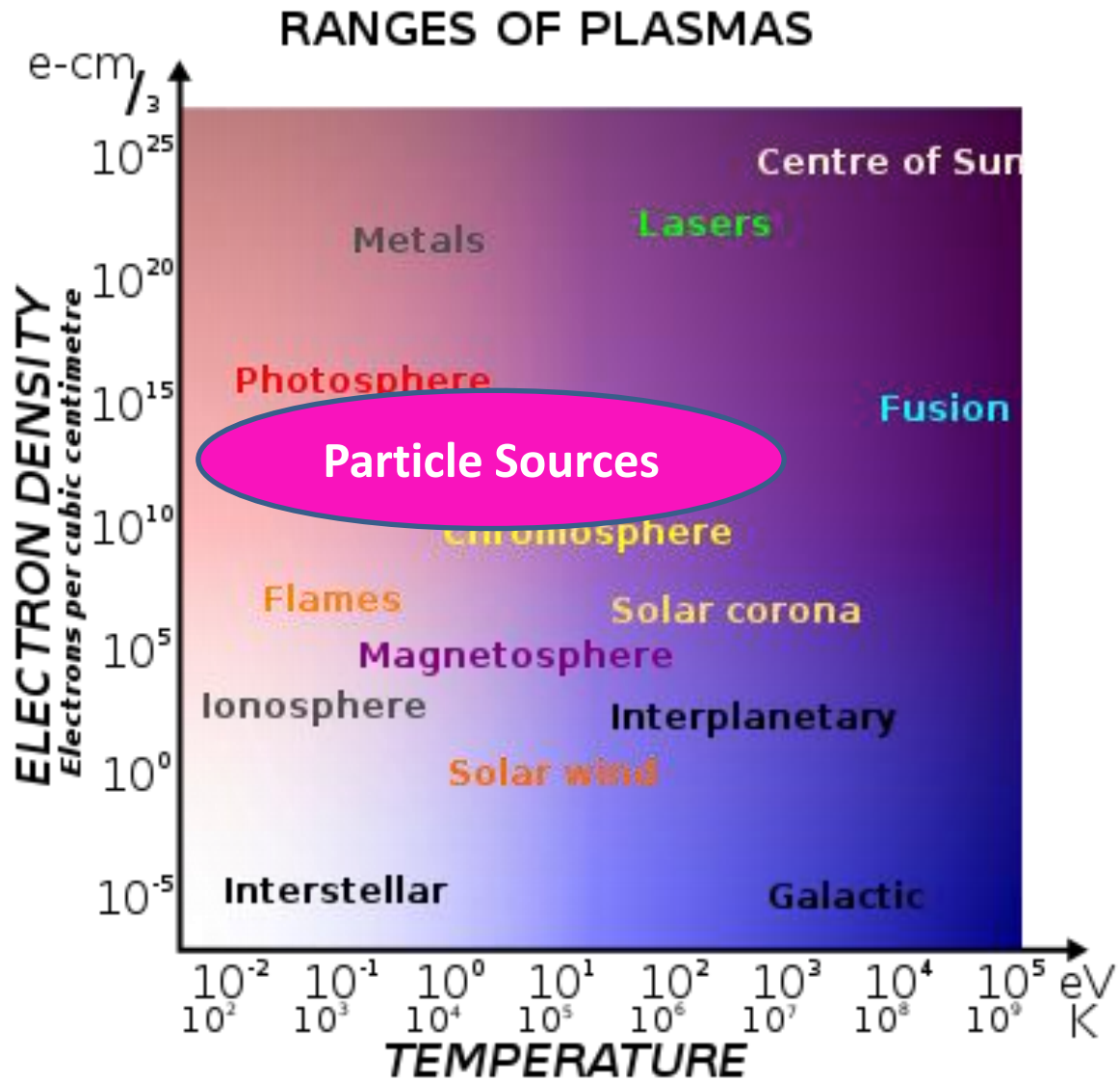
Temperature, *T* (eV)

T_e = temperature of electrons

T_i = temperature of ions

T_n = temperature of neutrals

11600°K = 1 eV

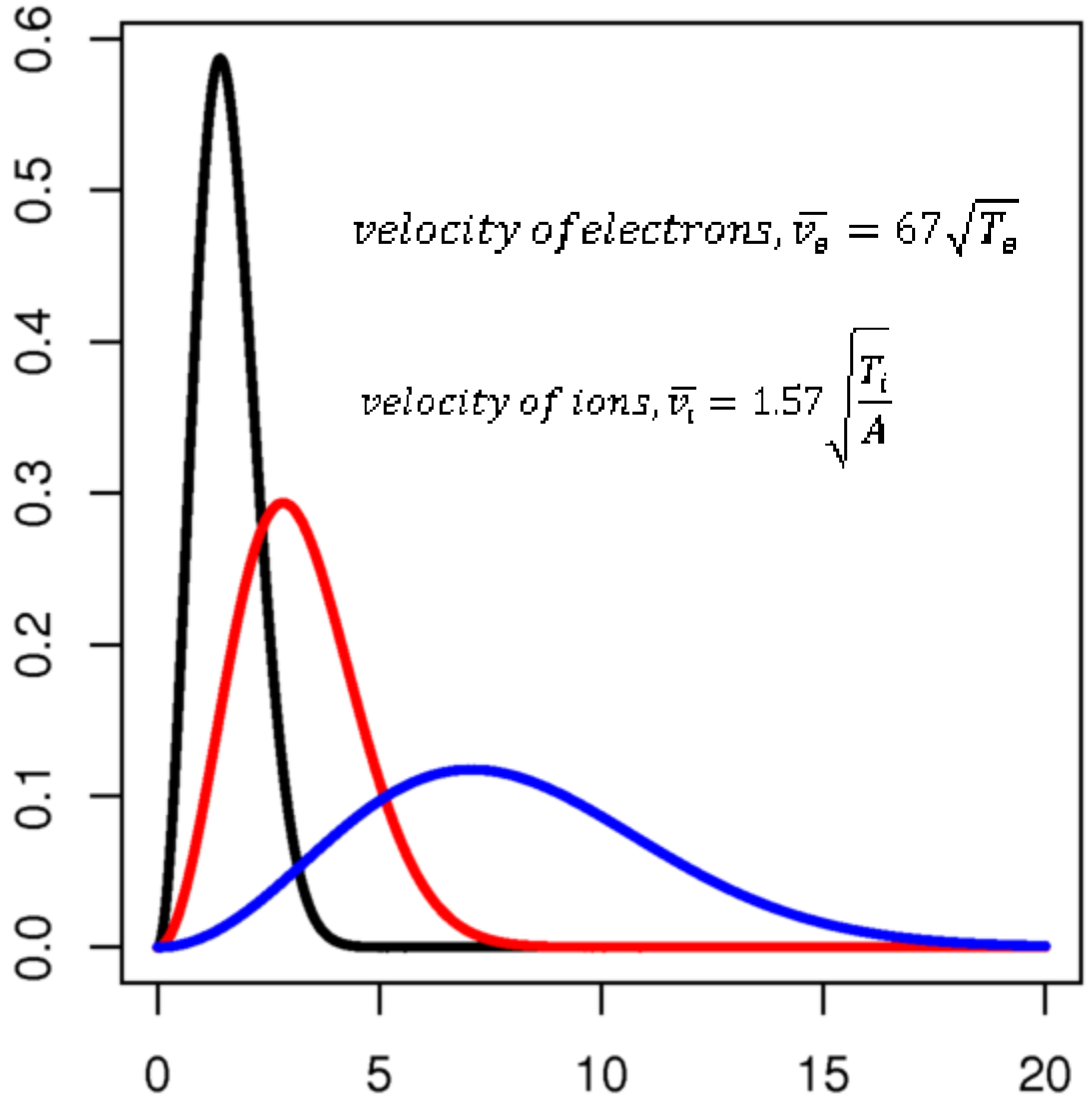

RANGES OF PLASMAS
e-cm/3
ELECTRON DENSITY
Electrons per cubic centimetre
10^25
10^20
10^15
10^10
10^5
10^0
10^-5
Centre of Sun
Lasers
Metals
Photosphere
Fusion
Particle Sources
Chromosphere
Flames
Solar corona
Magnetosphere
Ionosphere
Interplanetary
Solar wind
Interstellar
Galactic
10^-2 10^-1 10^0 10^1 10^2 10^3 10^4 10^5 eV
10^2 10^3 10^4 10^5 10^6 10^7 10^8 10^9 K
TEMPERATURE

Temperature Distribution

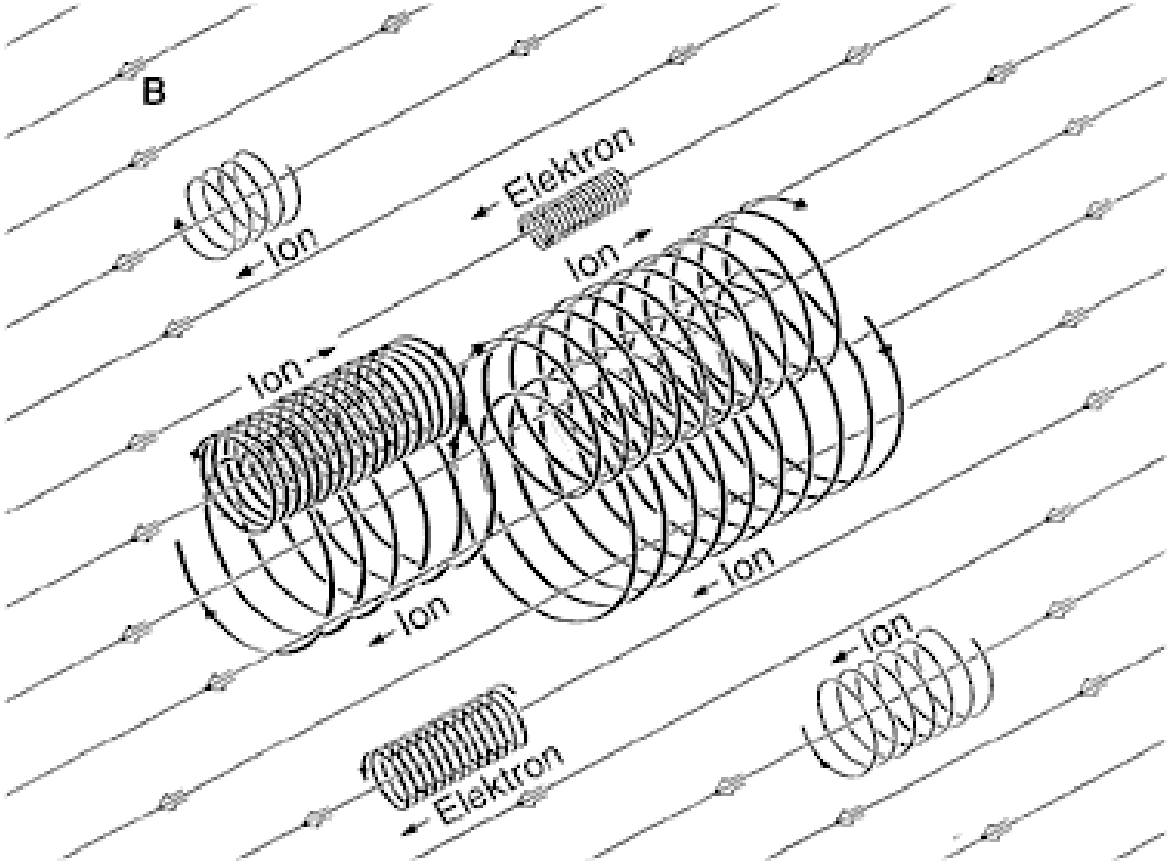
Maxwell Boltzmann statistics

In magnetic fields:

$$v_x \neq v_y \neq v_z$$

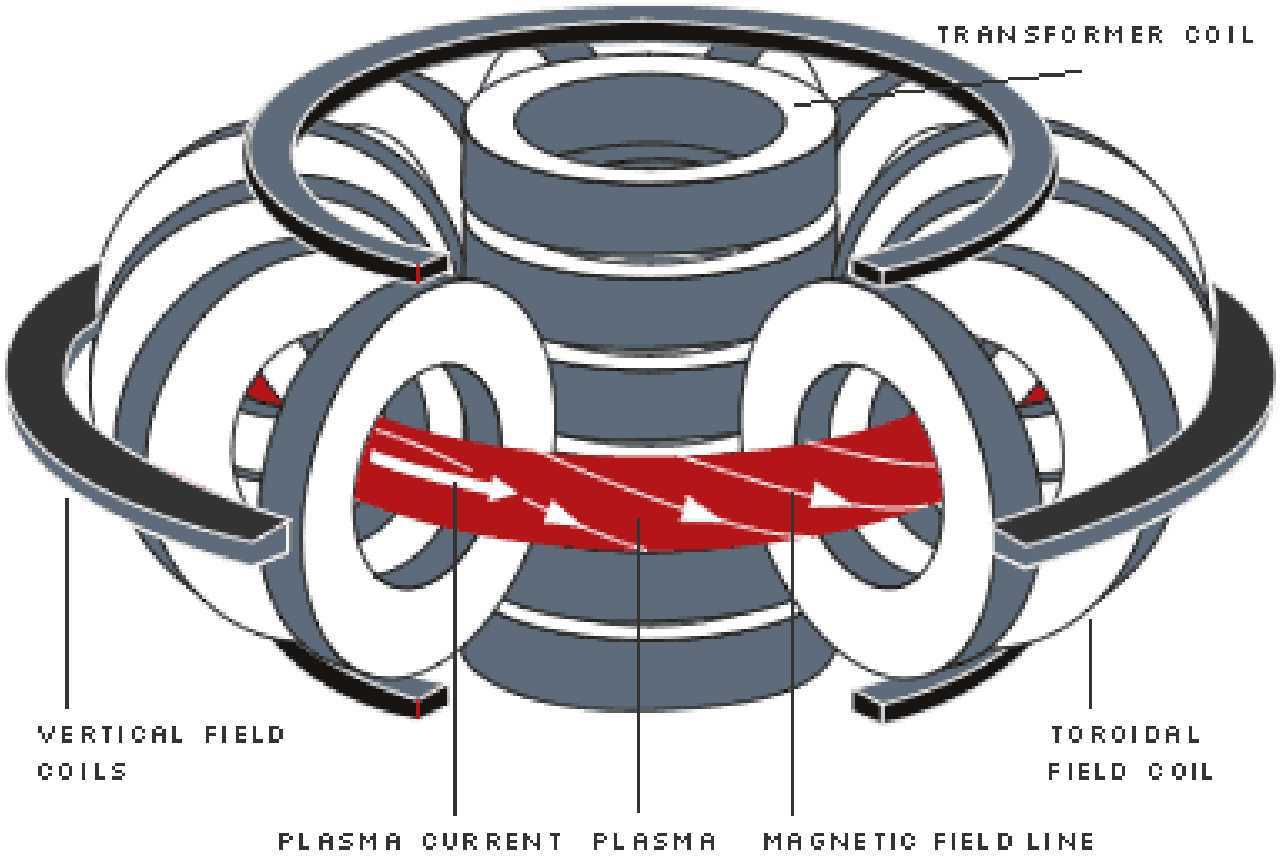


Magnetic Confinement

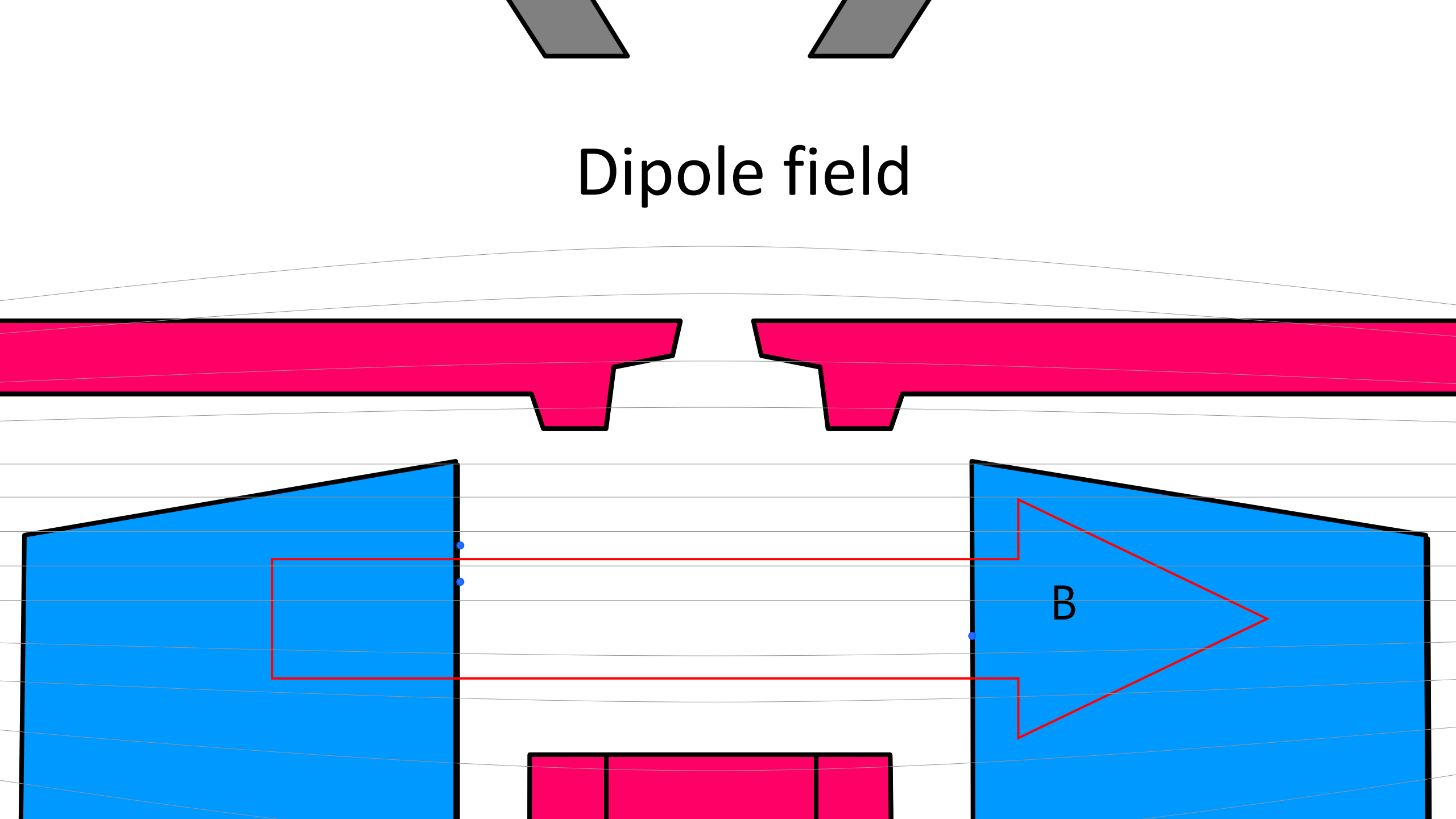


Particles spiral along magnetic field lines

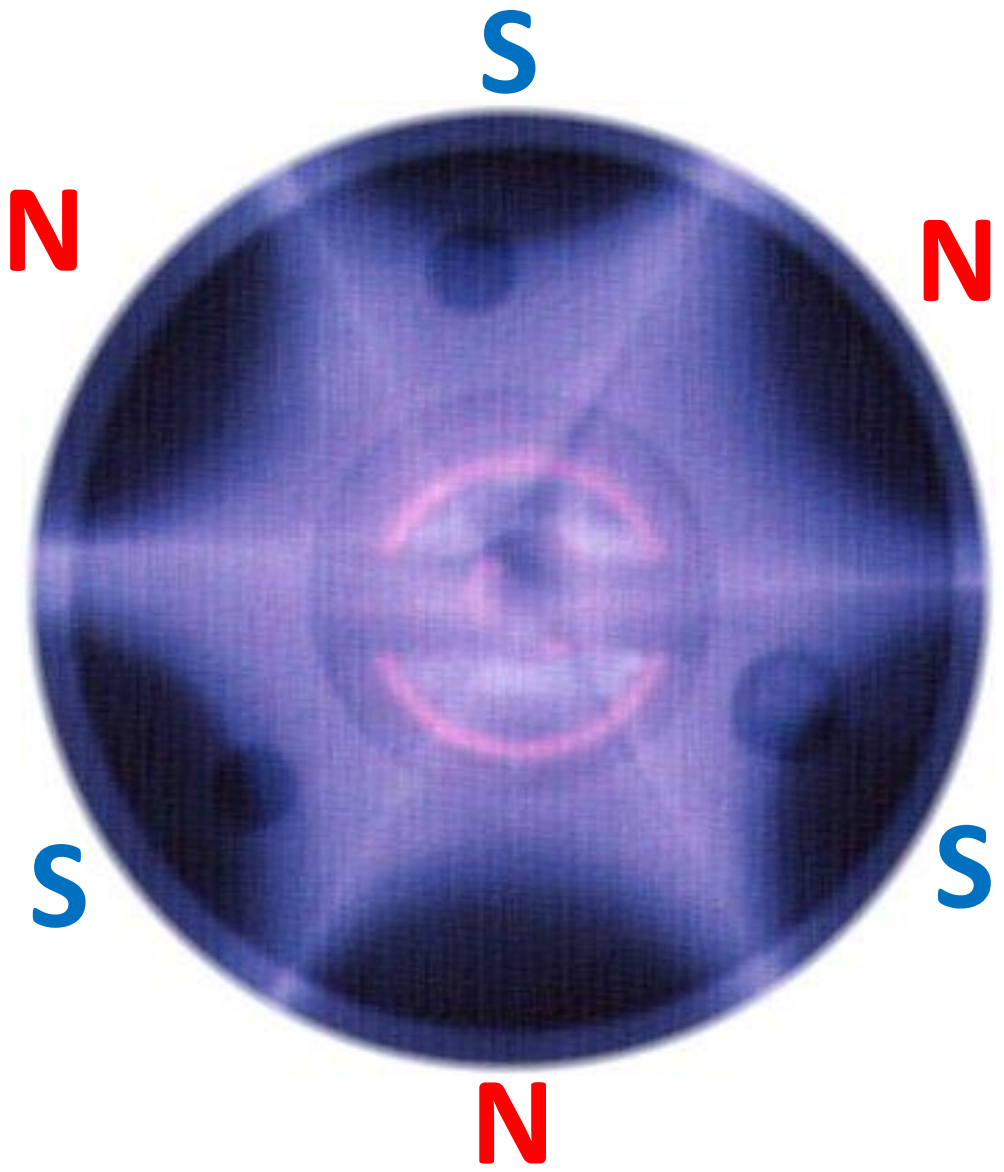
Solenoid field



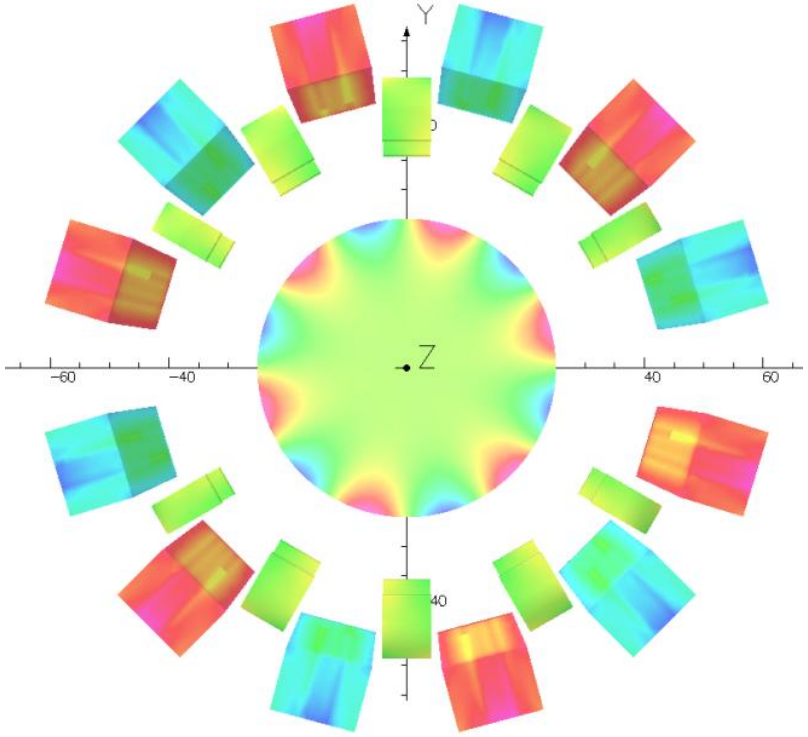
Dipole field

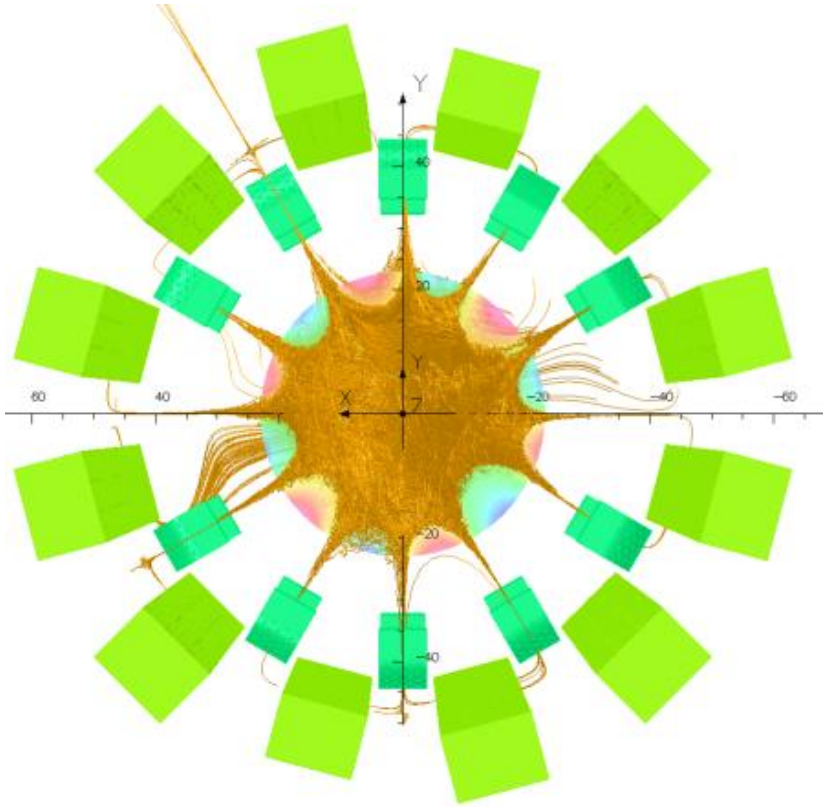


Hexapole



Multicusp Confinement





Percentage Ionisation

$$\frac{n_i}{n_i + n_n}$$

> 10 % → Highly Ionised
< 1 % → Weakly Ionised

Quasi Neutrality

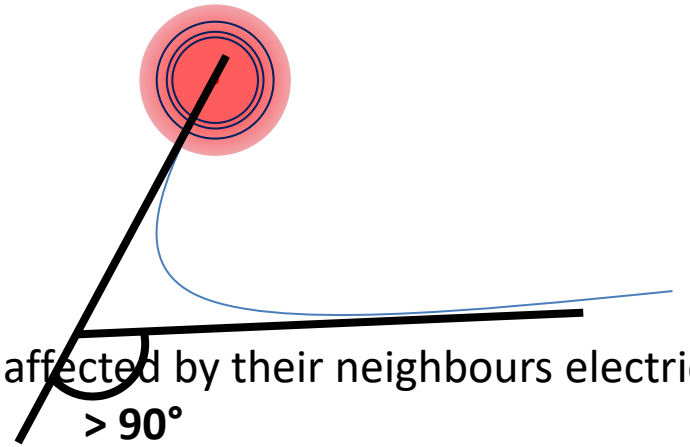
$$\sum q_i n_i = n_e$$

Collisions

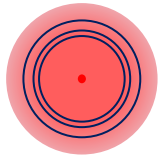
e-

Concept of mean free path does not work in a plasma

The average time it takes for a particle to be deflected by 90 °



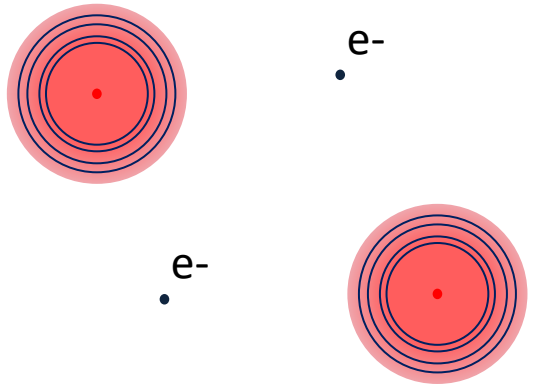
Charged particle trajectories are constantly affected by their neighbours electric fields



e-

Relaxation time = 90° deflection time

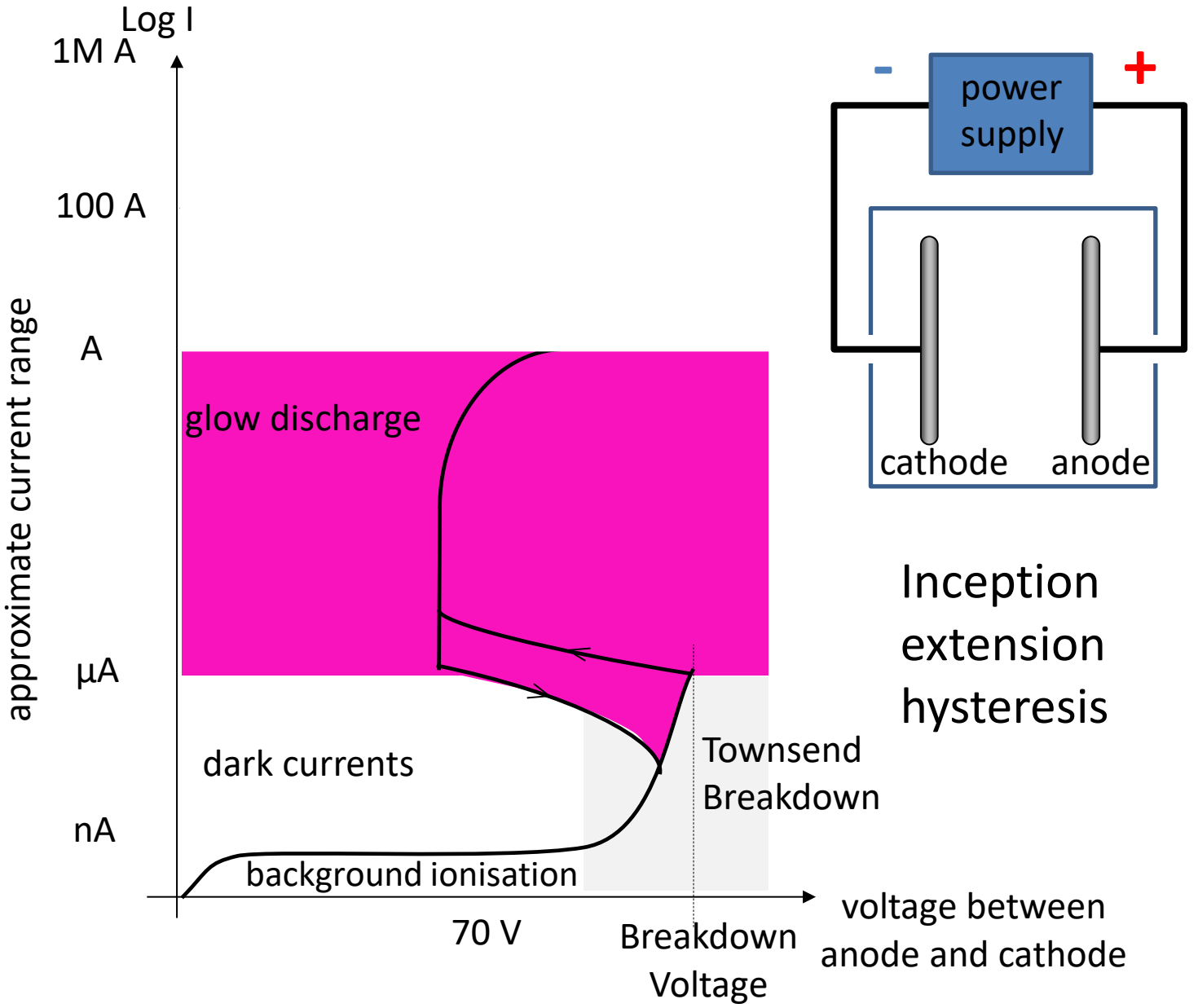
Debye Length



$$\lambda_D = \sqrt{\frac{\epsilon_0 k T_e}{n_e q_e{}^2}}$$

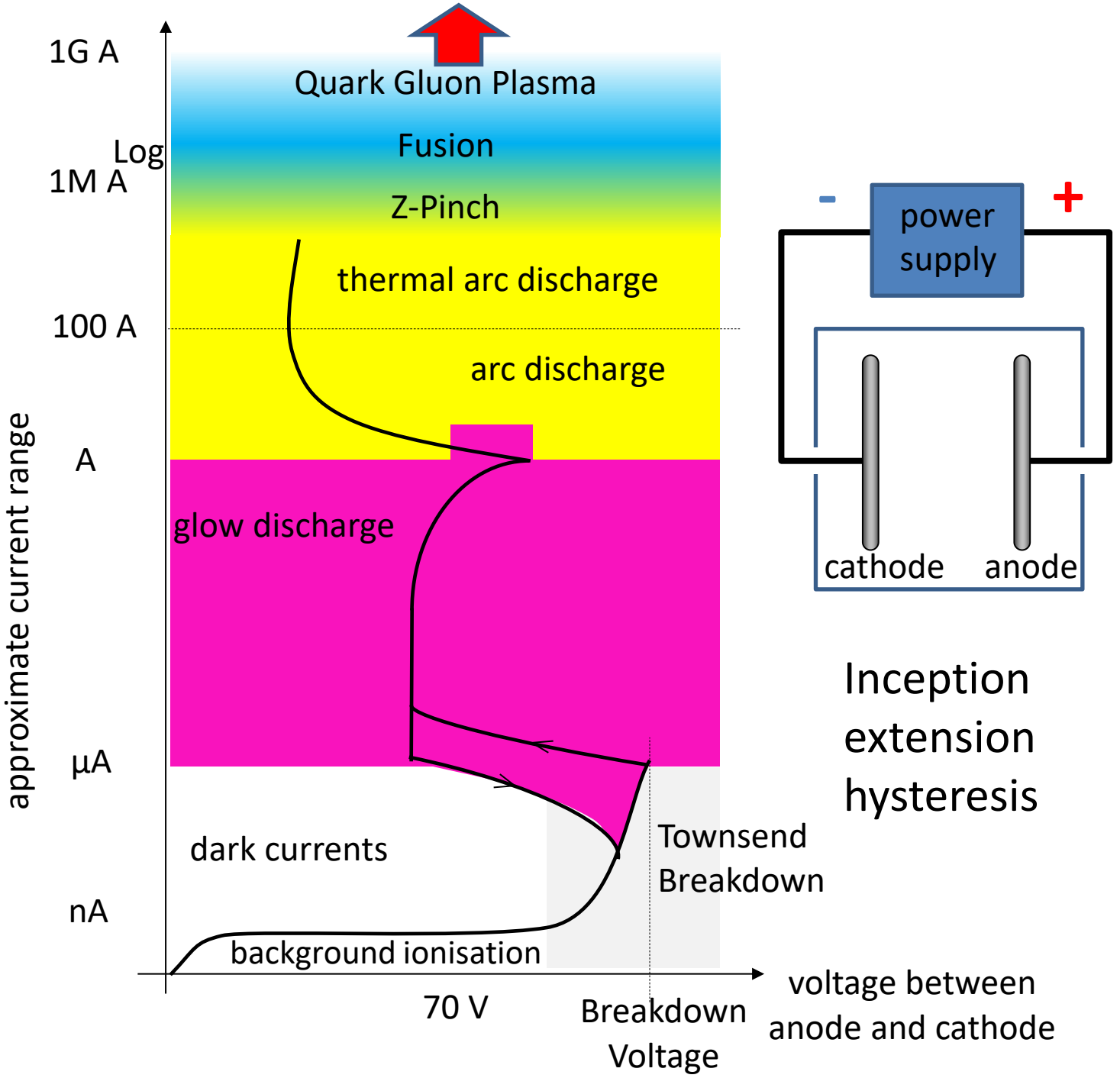
Electrical Discharges

If the pressure is low enough

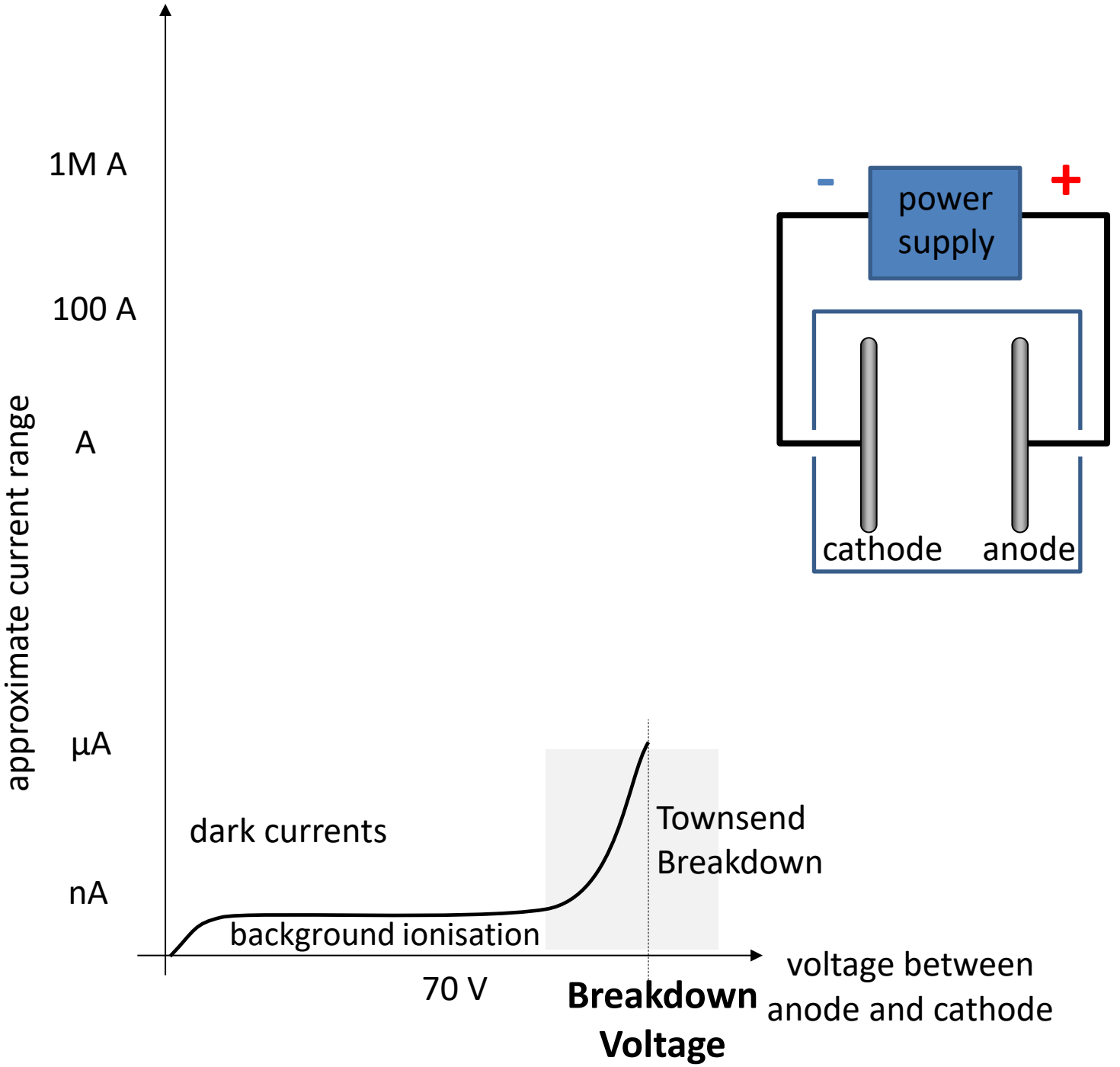


Inception
extension
hysteresis

If the pressure is low enough



Inception
extension
hysteresis


1M A
100 A
A
µA
nA
approximate current range
dark currents
background ionisation
Townsend
Breakdown
70 V
Breakdown
Voltage
voltage between
anode and cathode
-
+
power
supply
cathode
anode

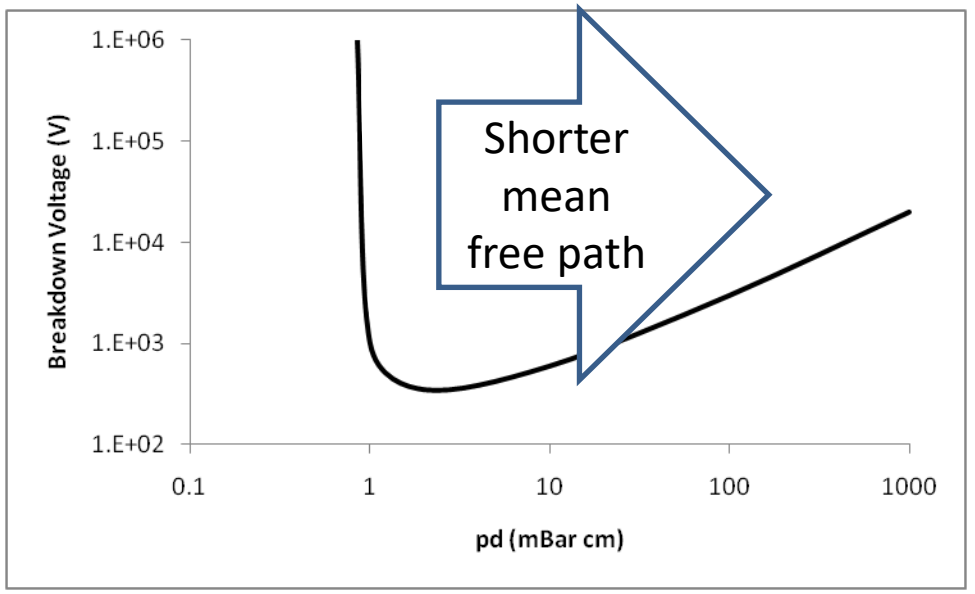
Breakdown strength of Air

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 $kVmm^{-1}$

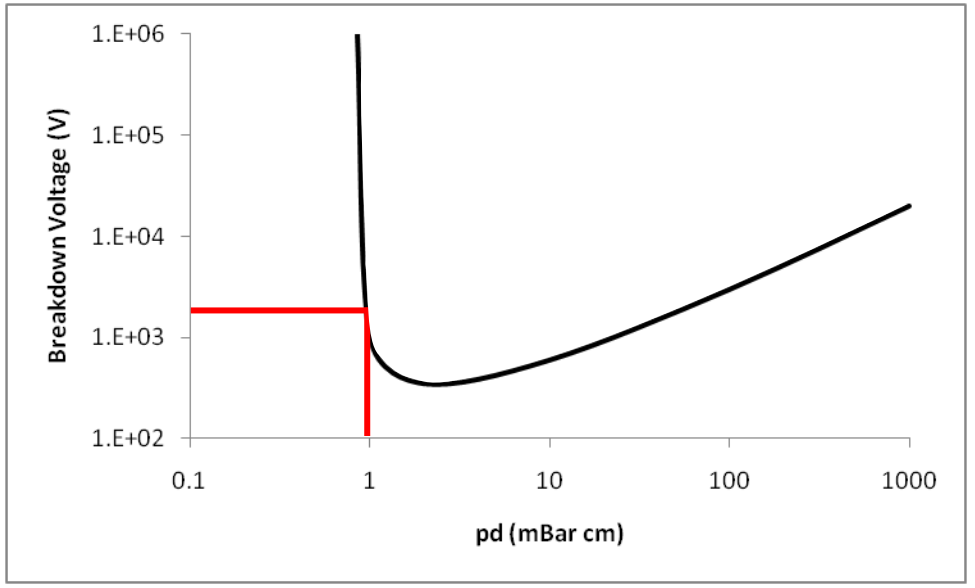
Paschen Curve

Friedrich Paschen 1889



Paschen Curve

Friedrich Paschen 1889

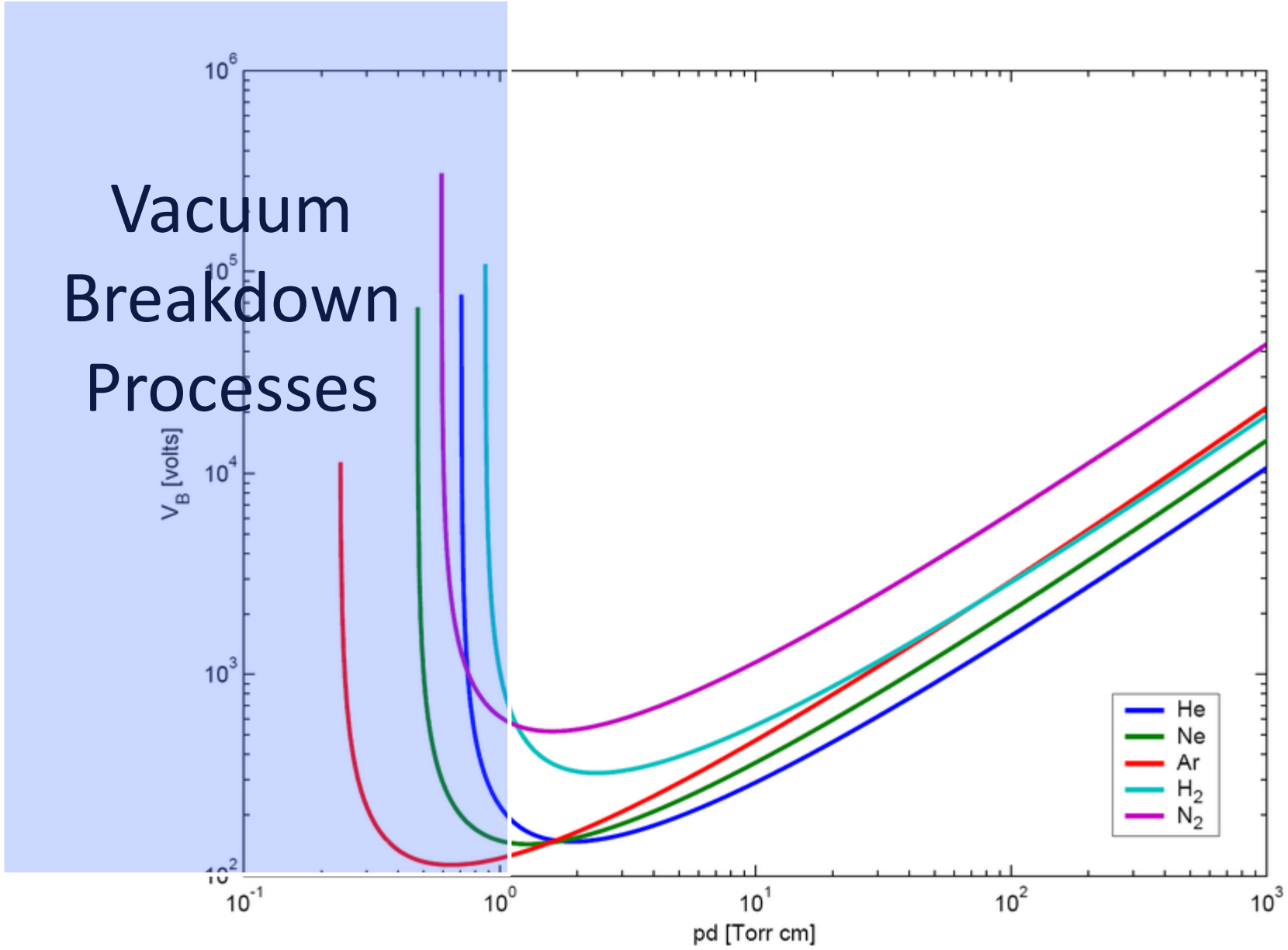


Operating just below the Paschen Minimum:

Longer gaps have

lower breakdown voltages!

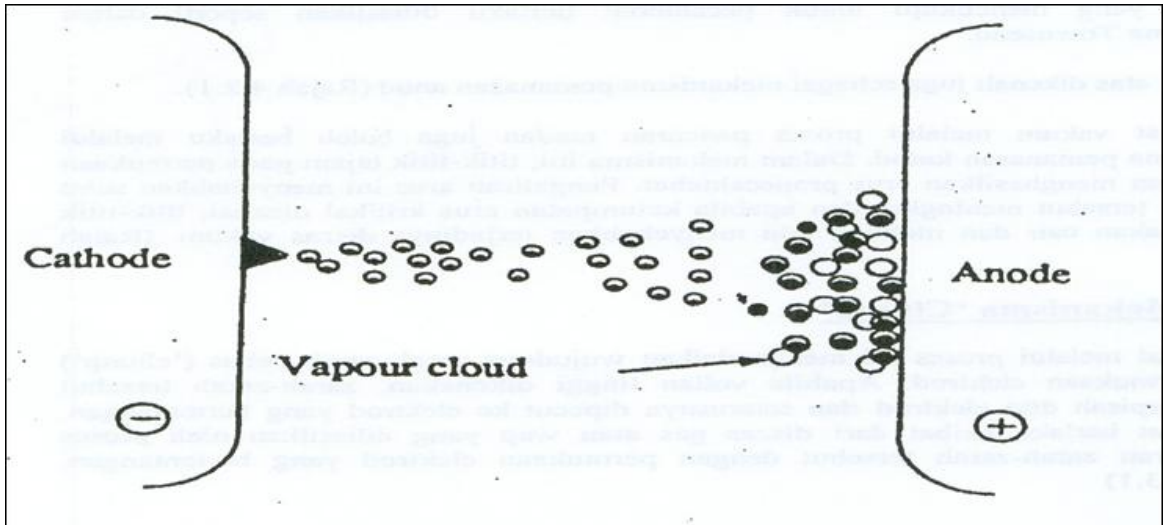
Vacuum Breakdown Processes



Vacuum Breakdown

Where do the charge carriers come from?

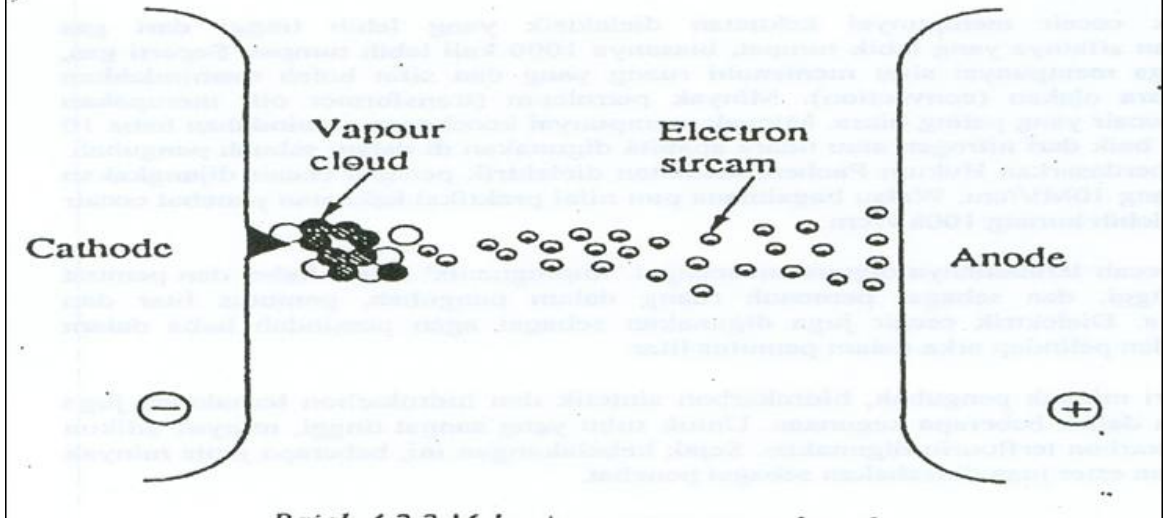
Insulating micro-inclusions can also cause field enhancement



Rajah 4.2.1 Mekanisma pemanasan anod

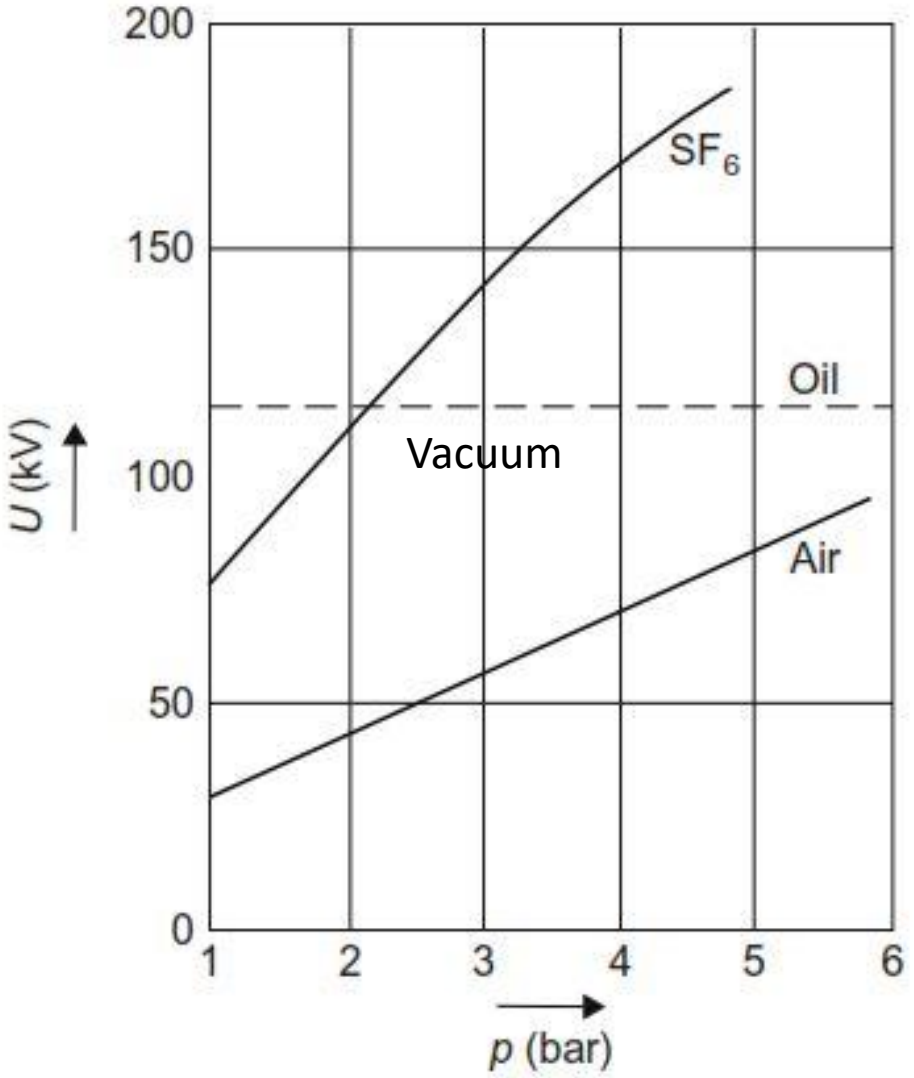
Conducting particles from anode

Conducting particles from cathode



If the timing is right (wrong!) alternating applied voltage can cause multipactoring in RF systems-
A resonant electron breakdown!

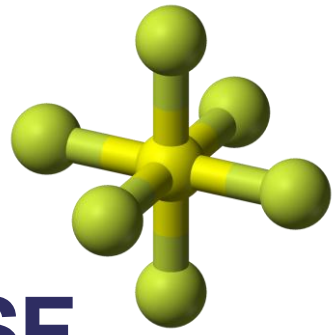
What about other insulating media?



- Sulfur hexafluoride (SF_6)
- Oil

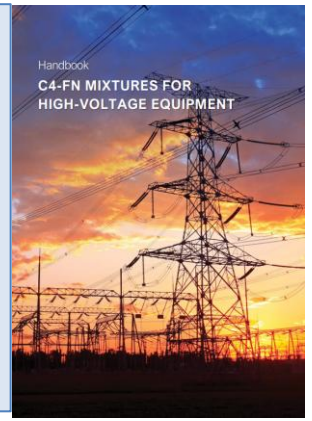
Sulfur hexafluoride (SF_6)

SF_6 is the most potent greenhouse gas:
1 kg SF_6 "lost" = 23 tonnes of CO_2
stays in the atmosphere for 3,200 years



SF_6

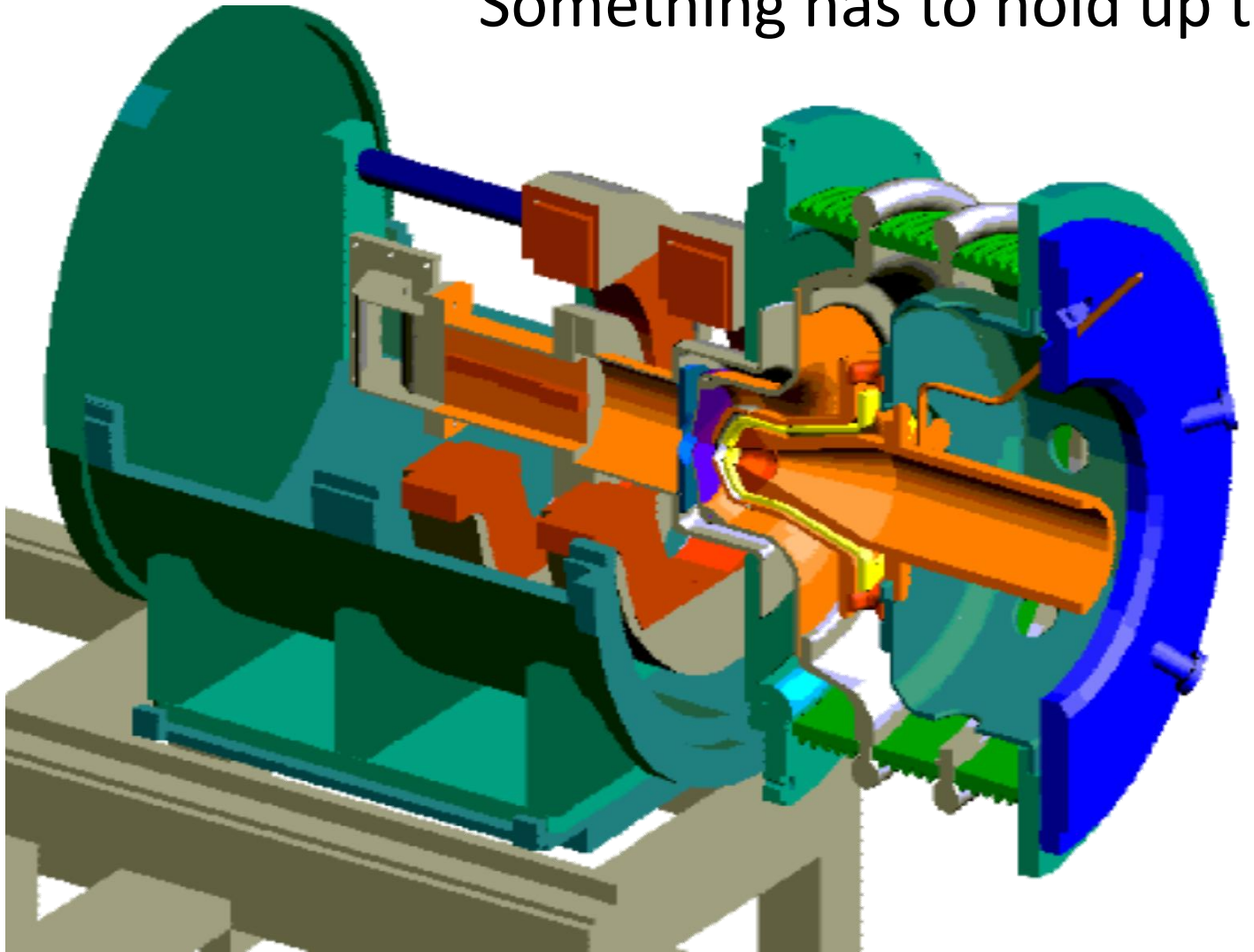
A possible solution is to modify the system to use a modern alternative e.g.
C4-FN (fluoronitrile) mixture
(O_2 / CO_2 / N_2)



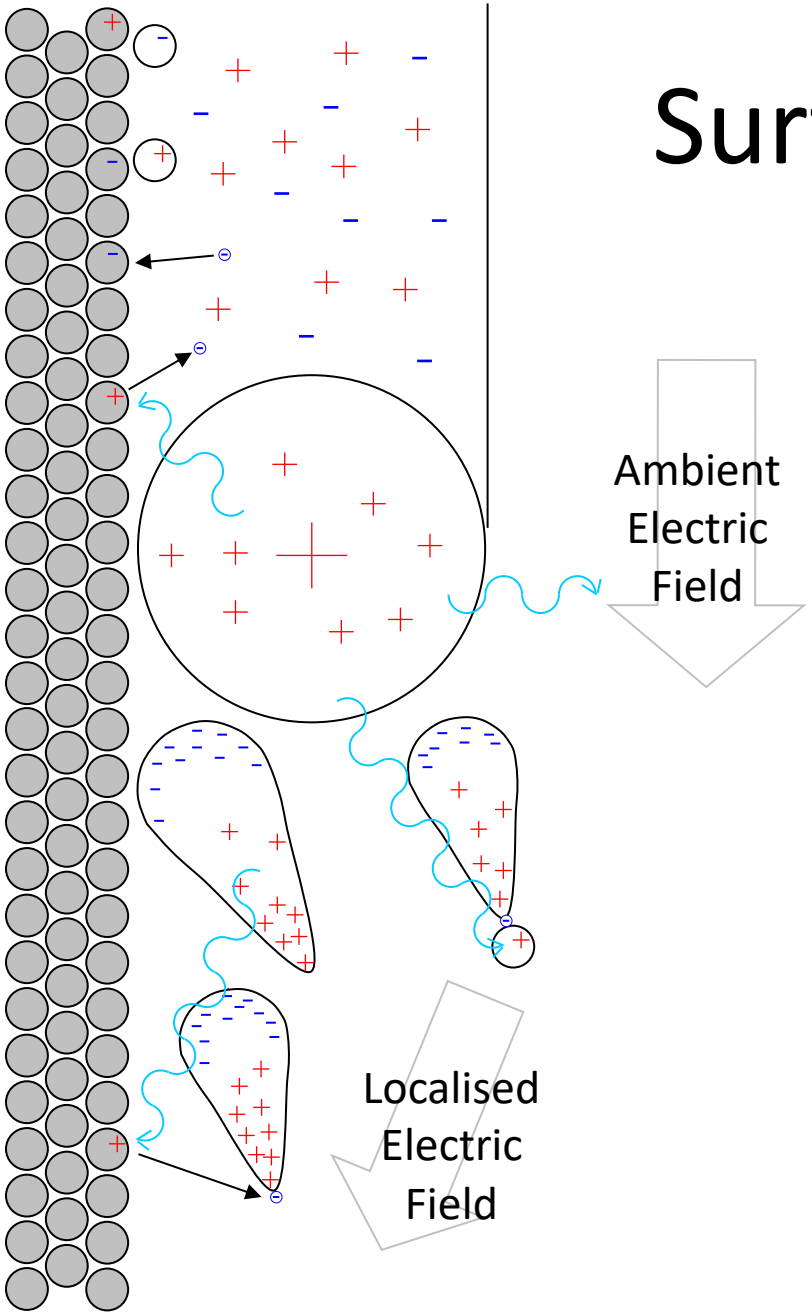
GE and Hitachi

Insulators

Something has to hold up the electrodes!

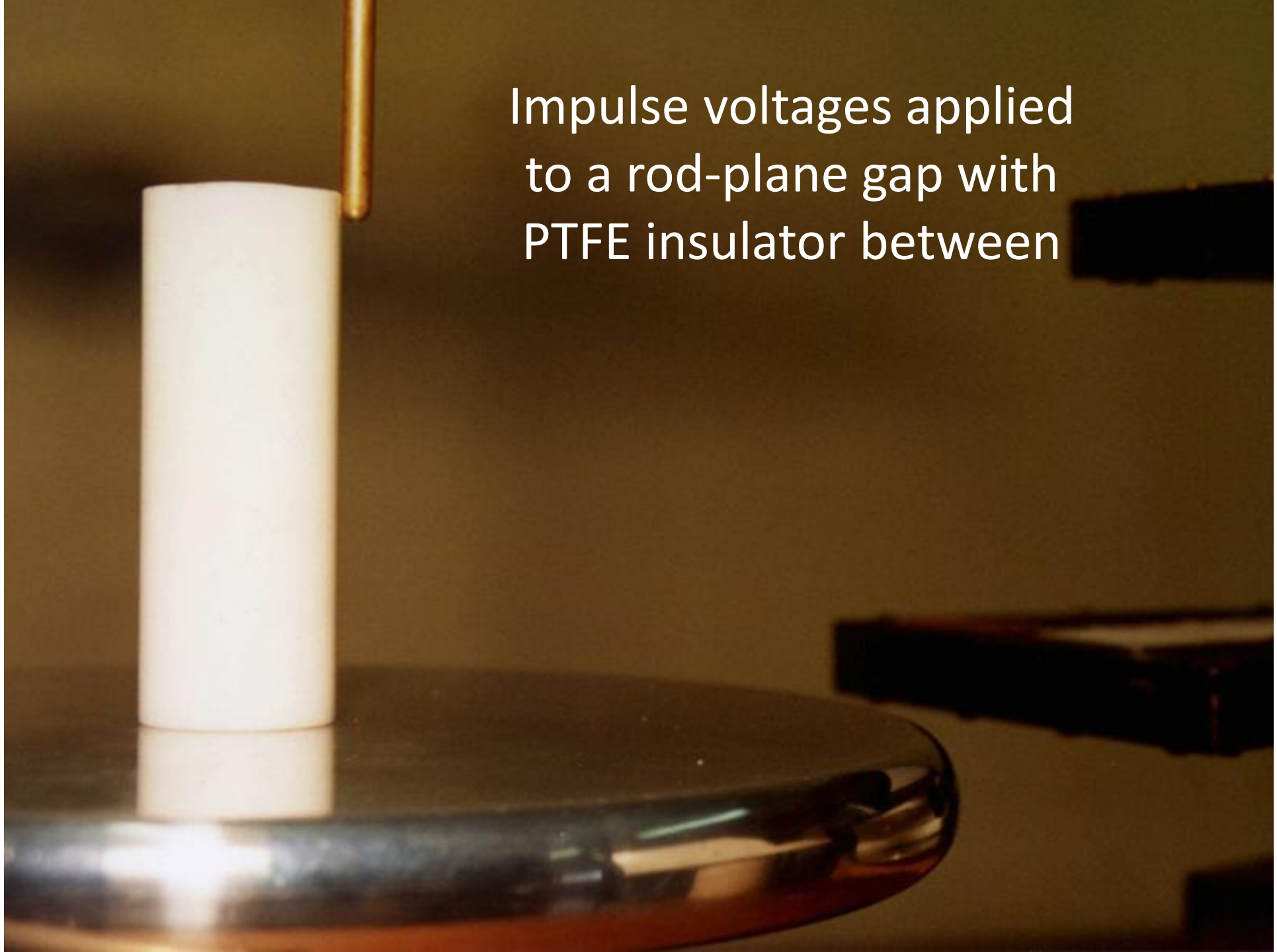


Surface Breakdown

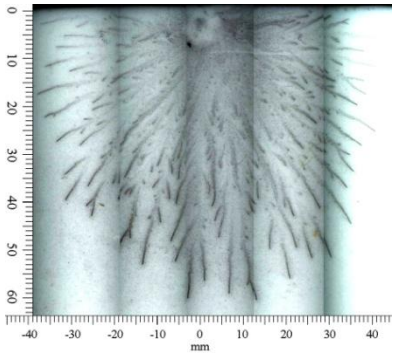


Insulator surfaces are the weakest part of the insulation system

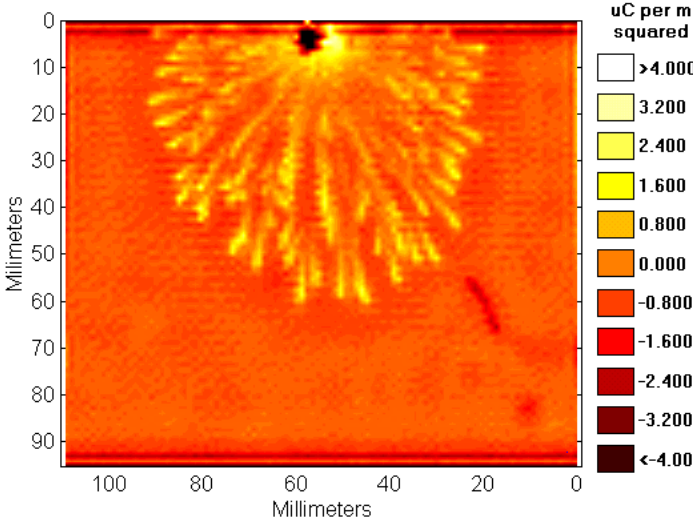
- Electrons
- Photons
- Neutral Gas Molecules
- Neutral Surface Molecules
- Positive Ions (Gas Molecules)
- Negative Ions (Gas Molecules)
- Positive Ions (Surface Molecules)
- Negative Ions (Surface Molecules)


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

Surface Charging

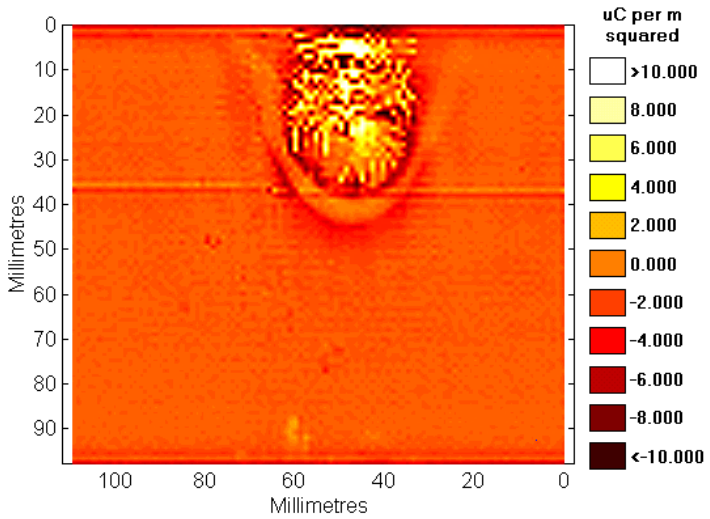


Dust Figure



Charge Distribution

+36 kV Impulse

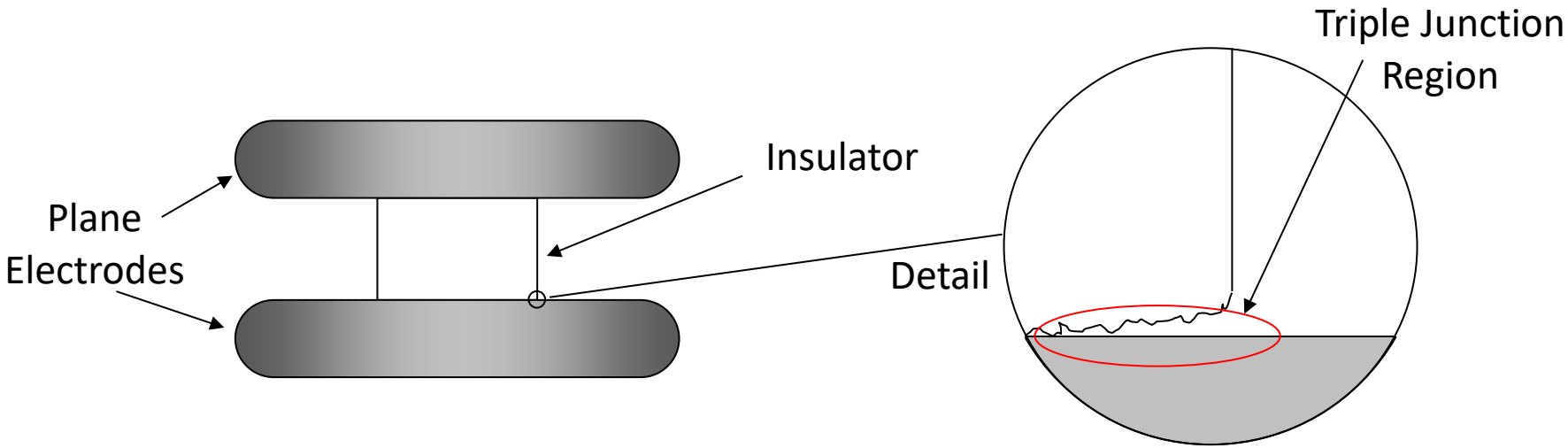


Charge Distribution

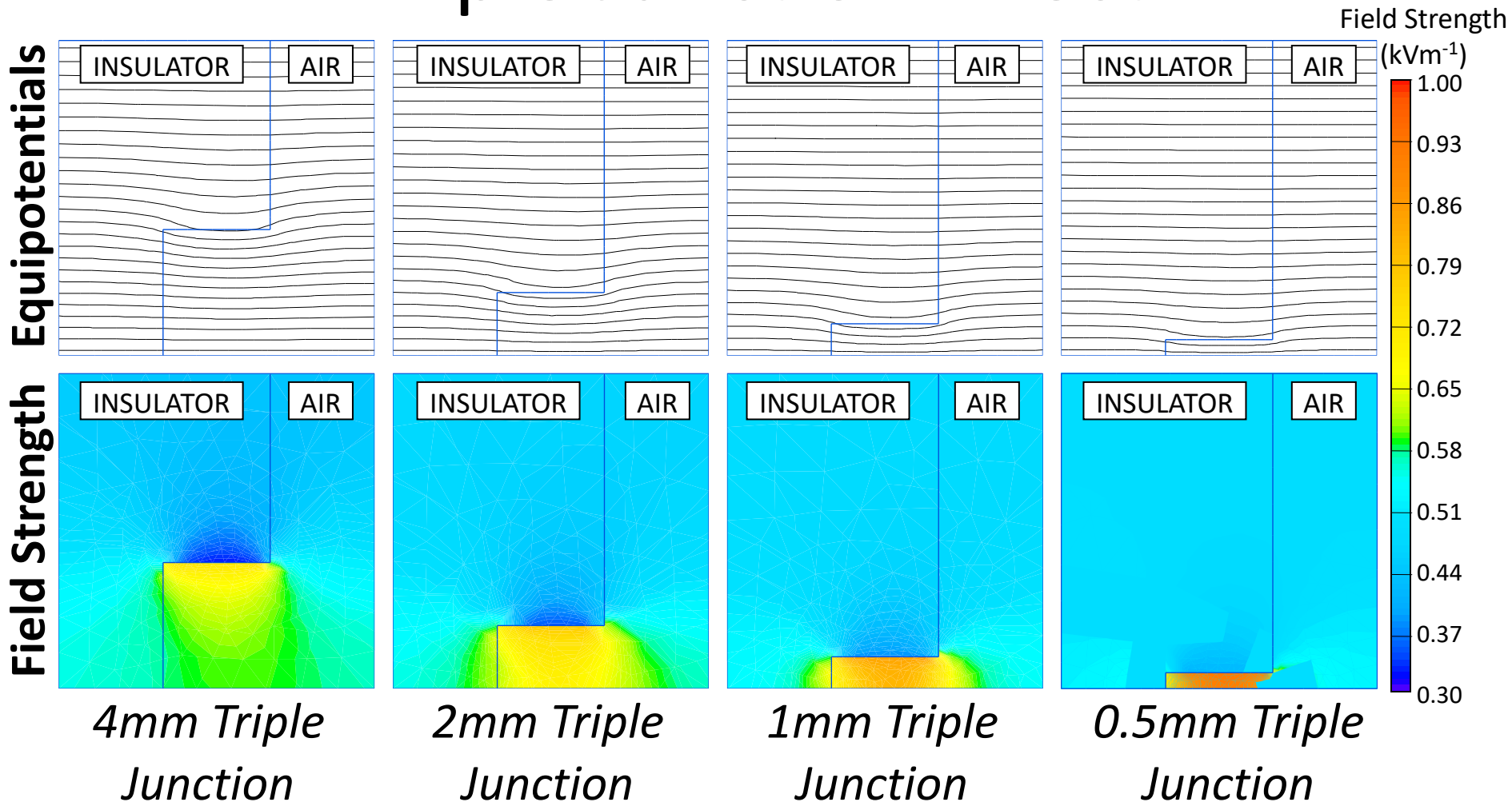
-70 kV Impulse

Polarity is very important if the gap is asymmetrical

Triple junctions always exist at some scale



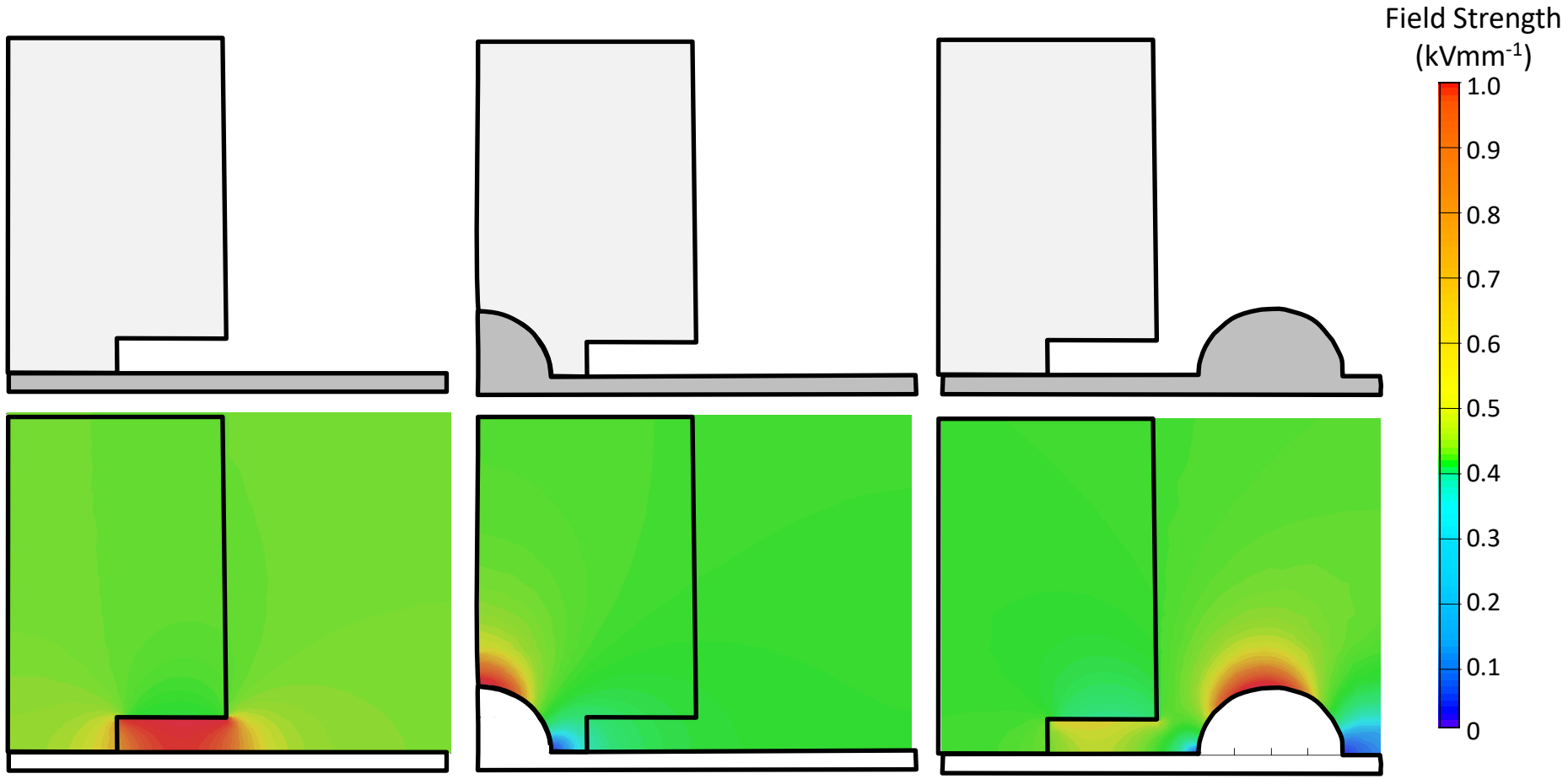
Triple Junction Effect



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

Triple Junction Screening

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



No Screening

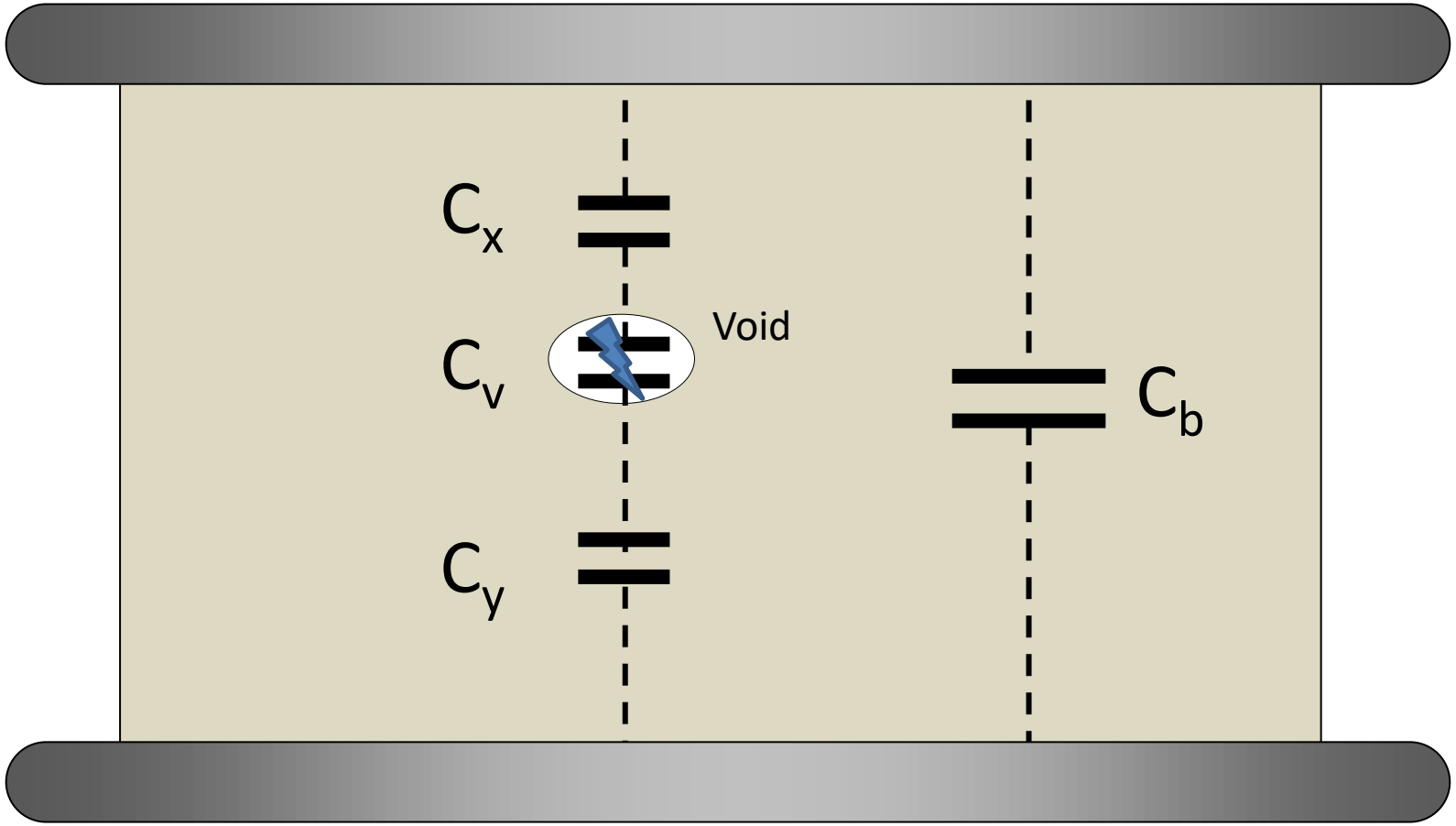
Inside Insulator

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
    - corona
    - partial discharge

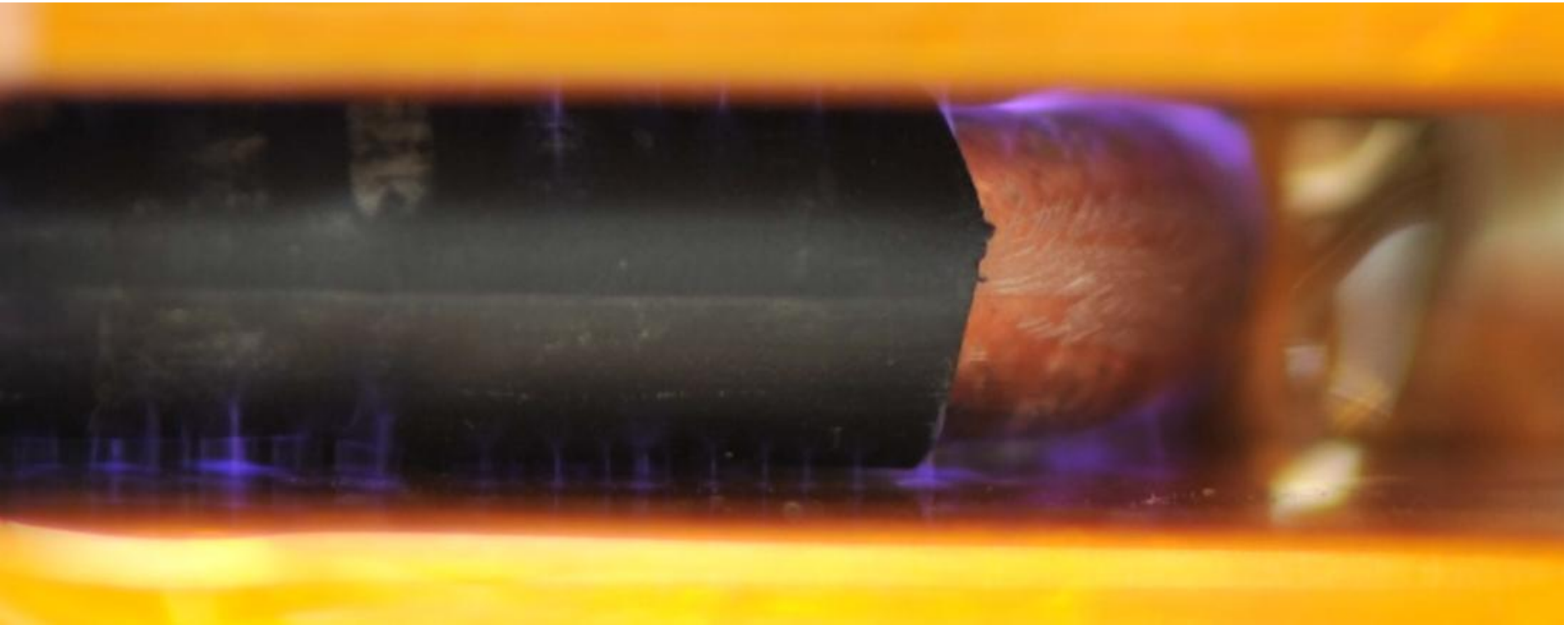
Partial discharges in voids



The largest volt drop is across the smallest capacitance

A cautionary tale

More insulation is not always a good idea…



Higher permittivity material pushes the field into the lower permittivity area

Insulator Surface Tracking

- Partial discharge activity can chemically degrade insulator surfaces
- Insulators degrade to carbon
- Conductive carbon deposits can enhance fields, increasing partial discharge activity
- Carbonised tracks can grow across high voltage gaps over time
- Cleanliness and pollution are important factors
- Introducing convolutions into the surface increases the tracking length

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

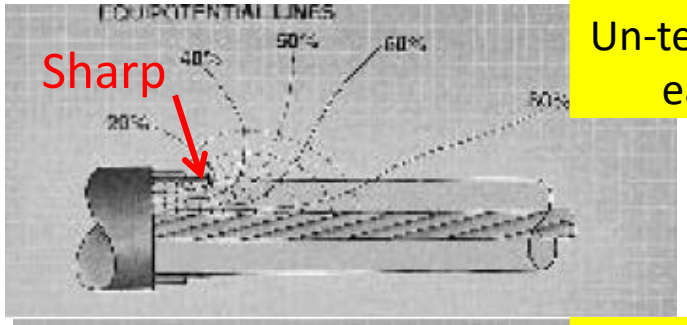
High voltage platforms don’t have to be too complicated, but...

Water and home-made insulators don’t mix

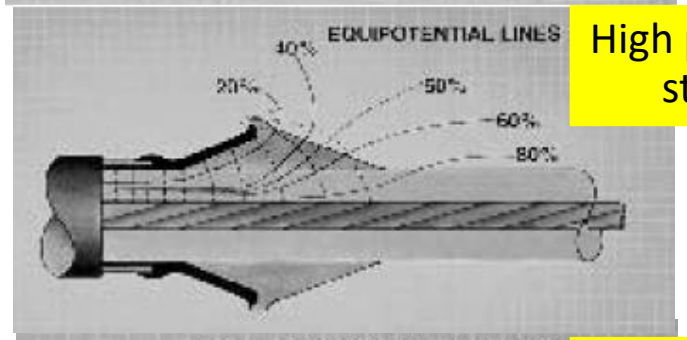
Commercial insulators are relatively cheap (≈€200) and will work in all conditions

Cable terminations

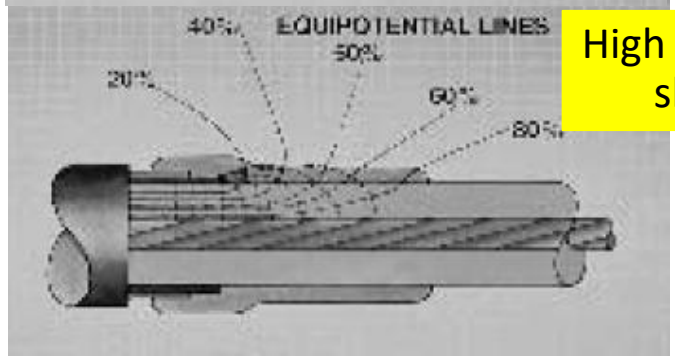
Correct electrostatic termination of high voltage cables is essential



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

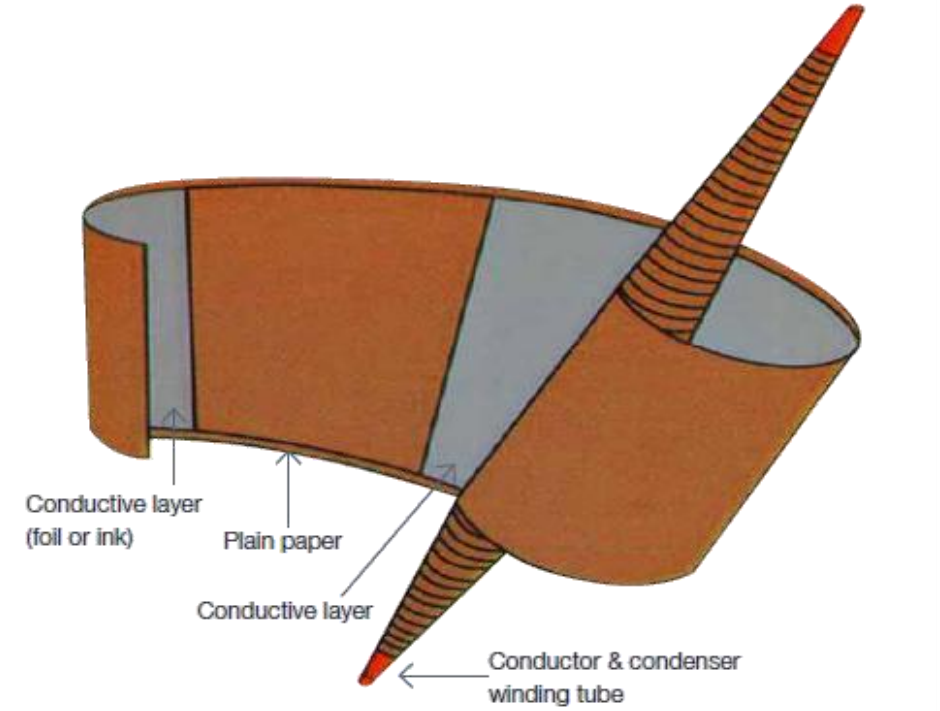
Connectors and Feedthroughs

Depends on...

- Application
- Maintenance
- Permanence
- Voltage

> 50 kV needs feedthroughs or bushings

Big Bushings

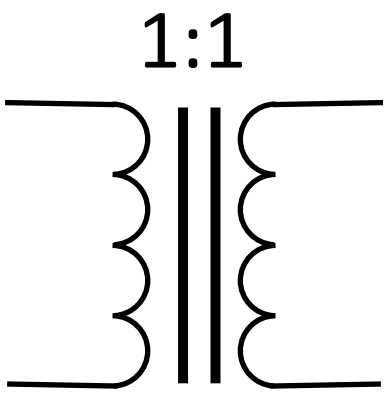


Isolated Power

How to get mains power
to equipment floating
on a HV platform?

Motor- alternator set

Waveguide DC break

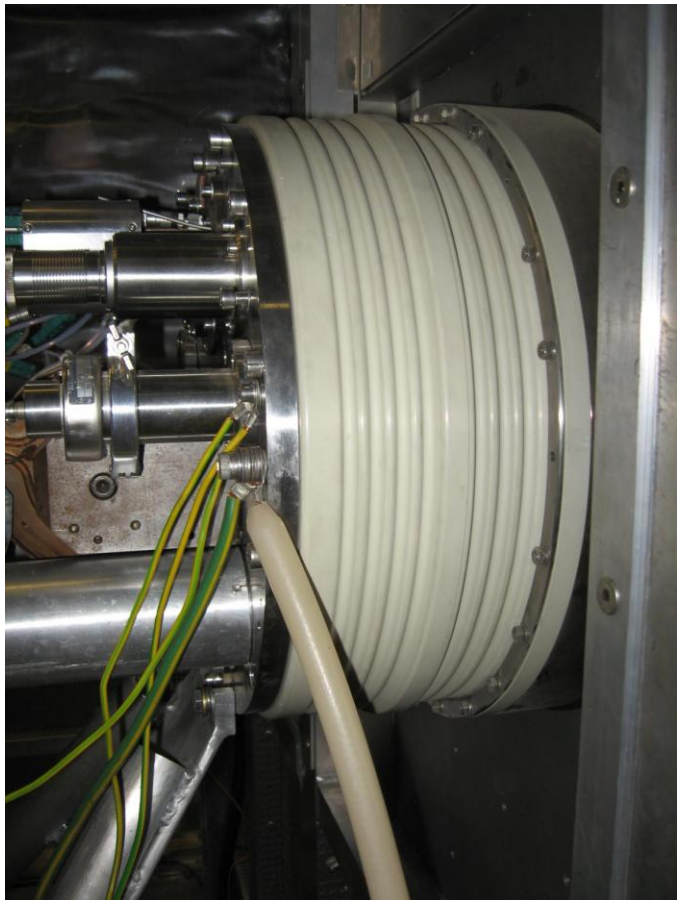


Isolation transformer

Earthing (Grounding)

- An earthing system should grow like a tree
- Provide a low impedance path to earth
- Avoiding parallel paths will prevent earth loops

Solid single point earth

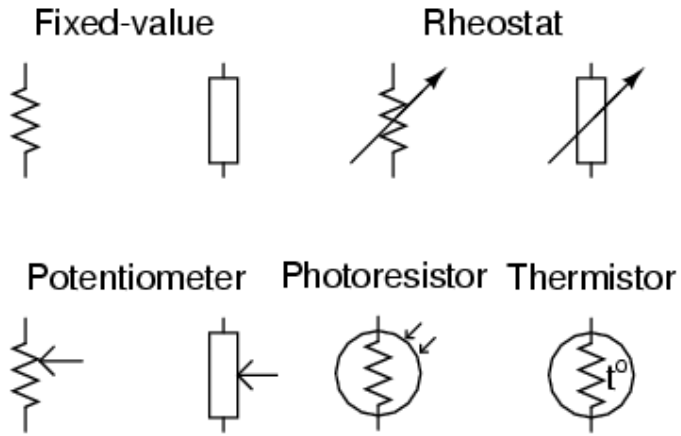


High voltage platform becomes “Local earth”

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

Resistors



Ohms law $V = IR$

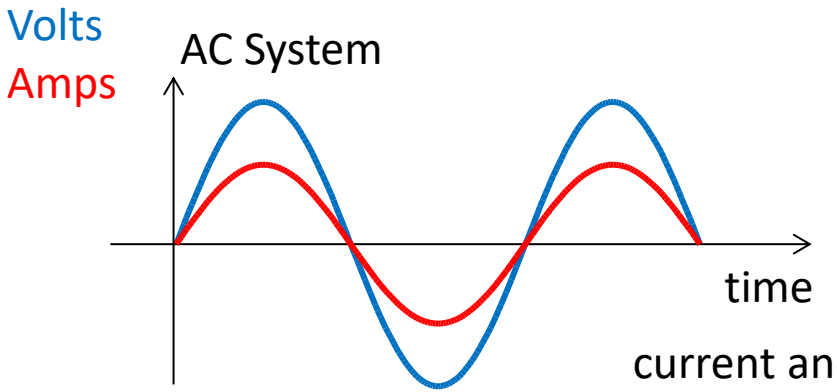
$Power = VI = I^2R = V^2/R$

Resistance in Ohms Ω

Power in Watts W

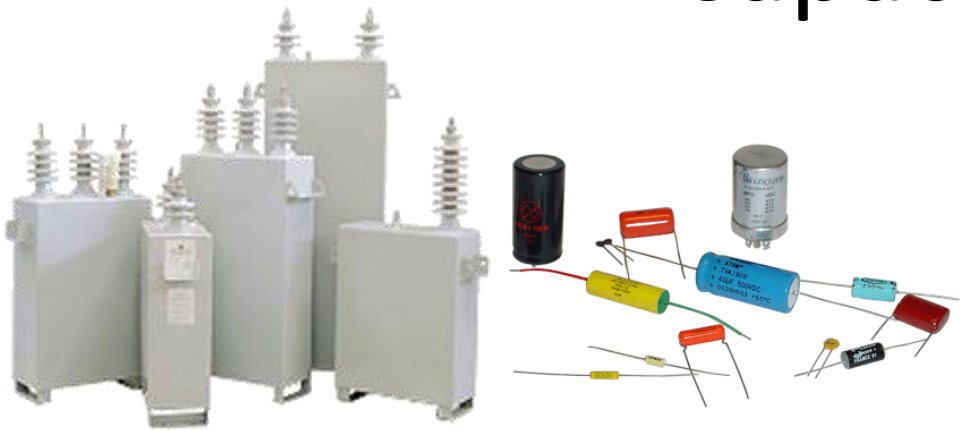
Voltage rating

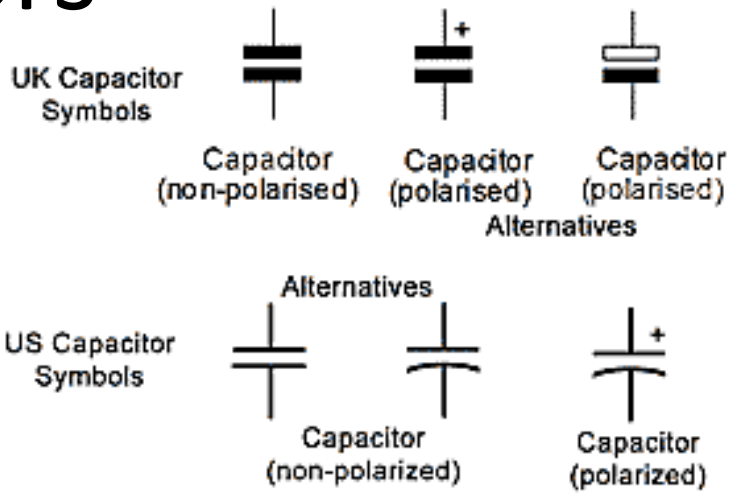
Tolerance in %



current and
voltage in phase

Capacitors





Capacitance in Farads, F

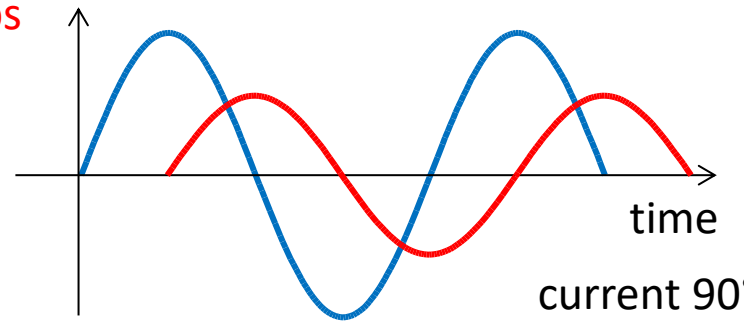
Frequency dependency $V = I X$

$V = I \frac{-j}{2\pi f C}$

High pass filters

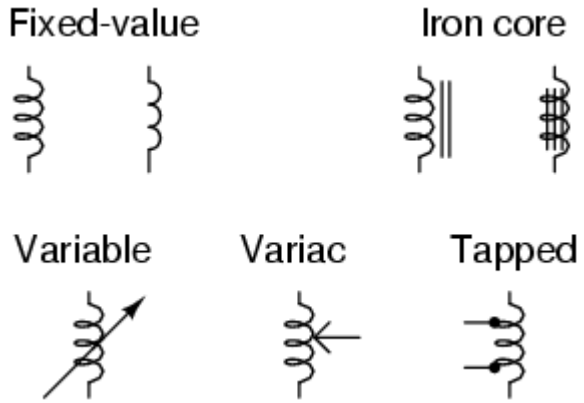
Volts

Amps



current 90° ahead of voltage

Inductors



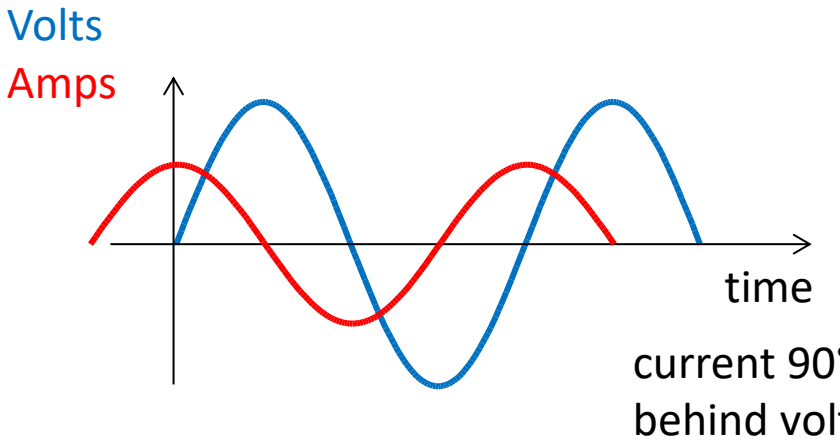
Frequency dependency

$V = I X$

$V = I\ j2\pi Lf$

Inductance in Henrys, H

Low pass filters

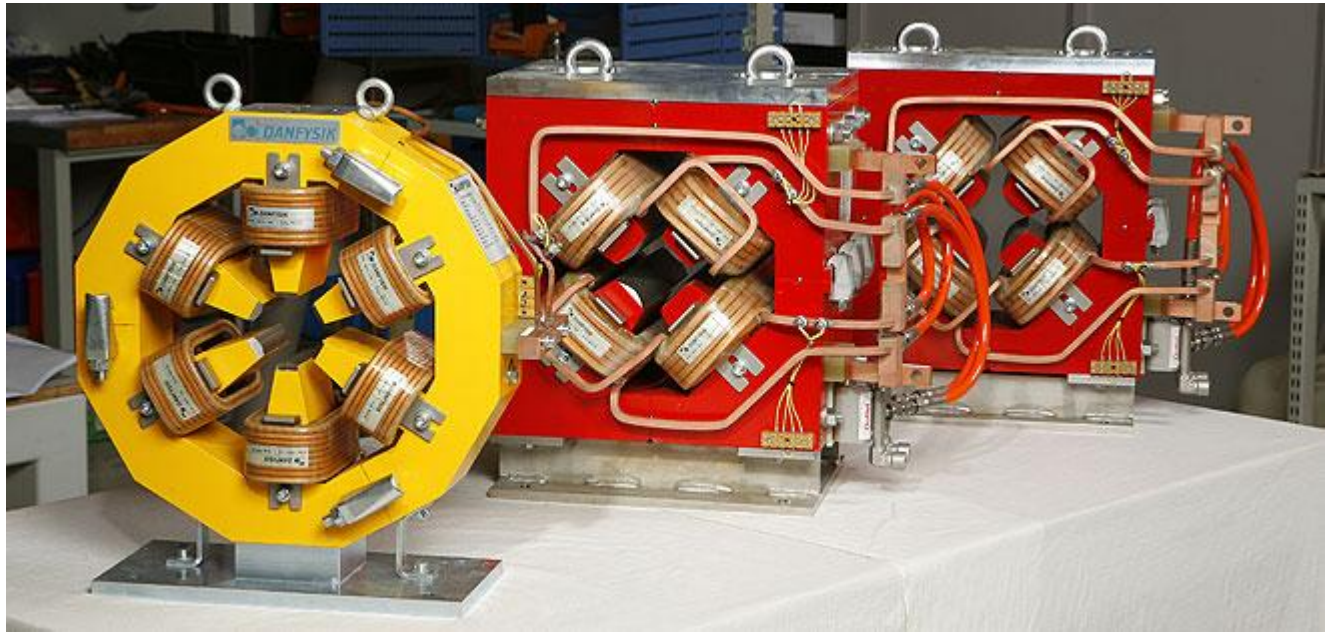


CIVIL

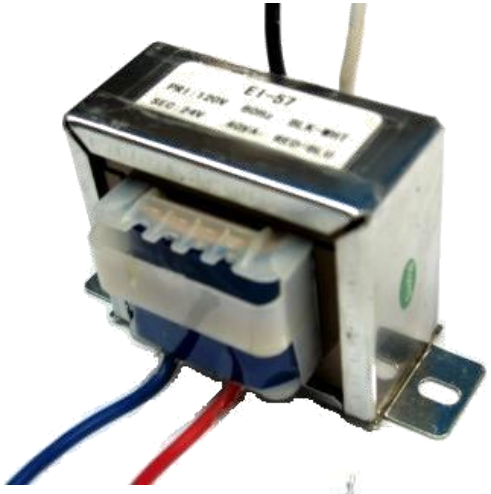
Particle Accelerator Magnets

Dipoles
Quadrupoles
Sextupoles
Octopoles

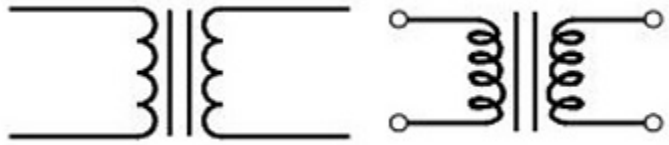
Inductors + small R (<1Ω)

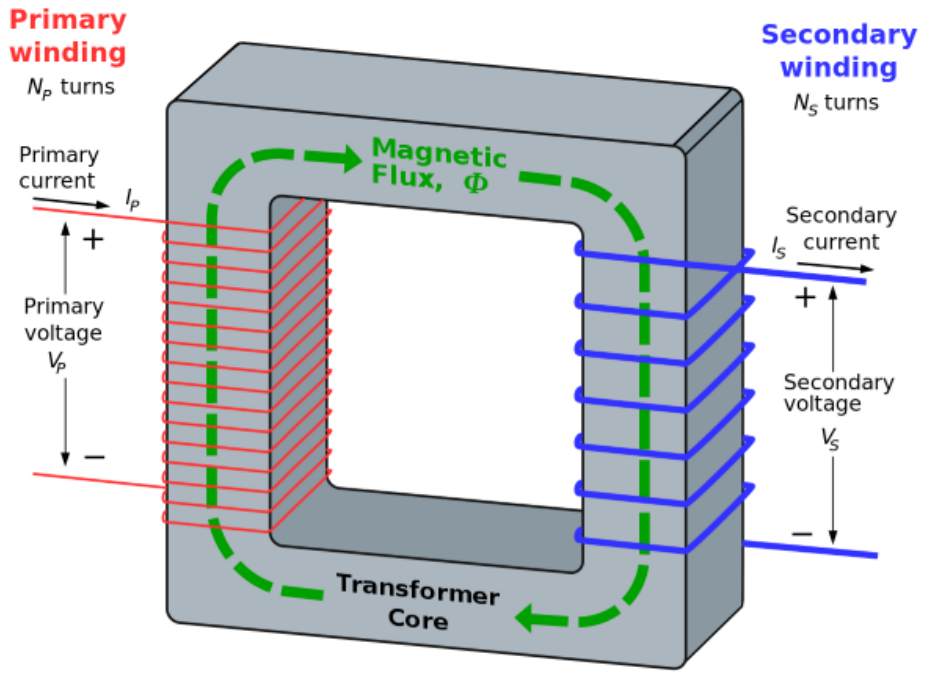


Transformers



Circuit diagram symbols





Turns ratio = $\frac{N_p}{N_s}$

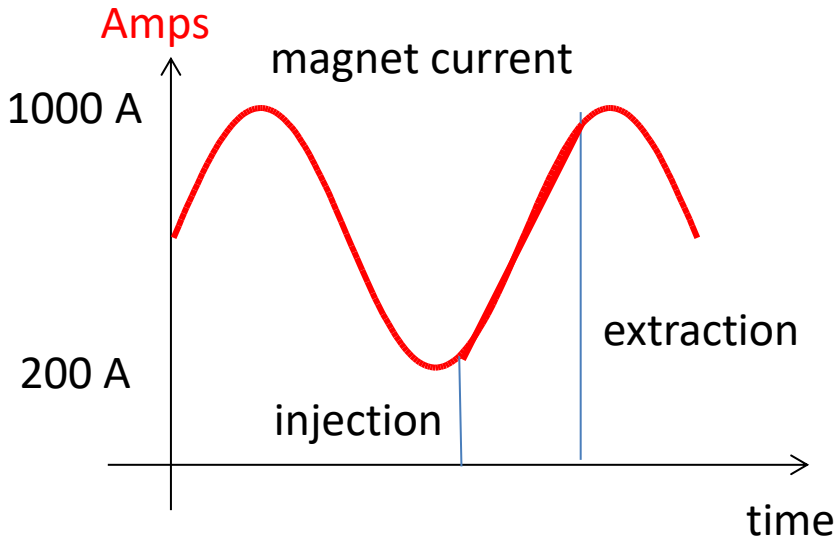
Inductors that see the load through the transformer

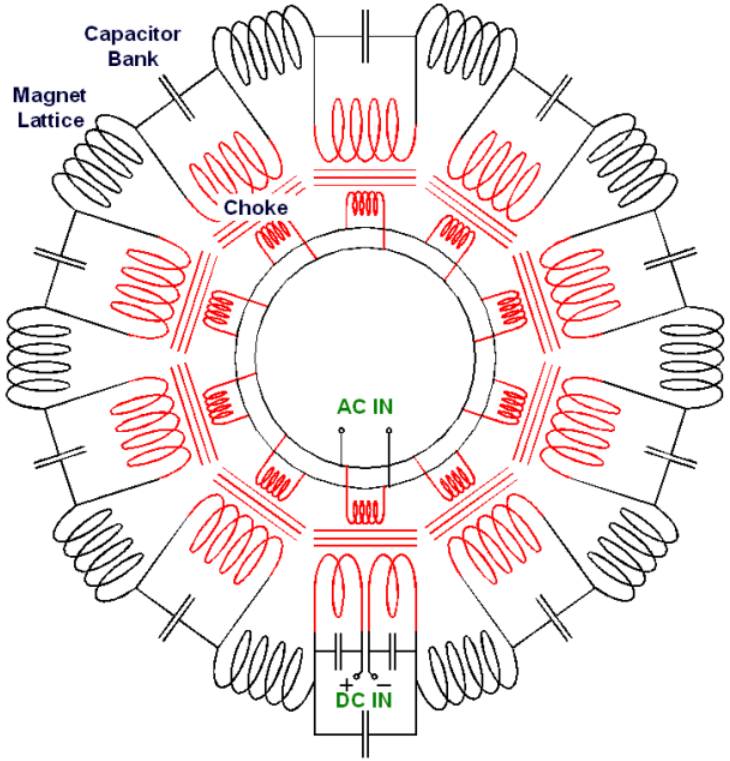
Resonance

ISIS White Circuit

30 tonne dipole magnet (X10)

Synchrotron needs a magnetic field that rises in a few ms:

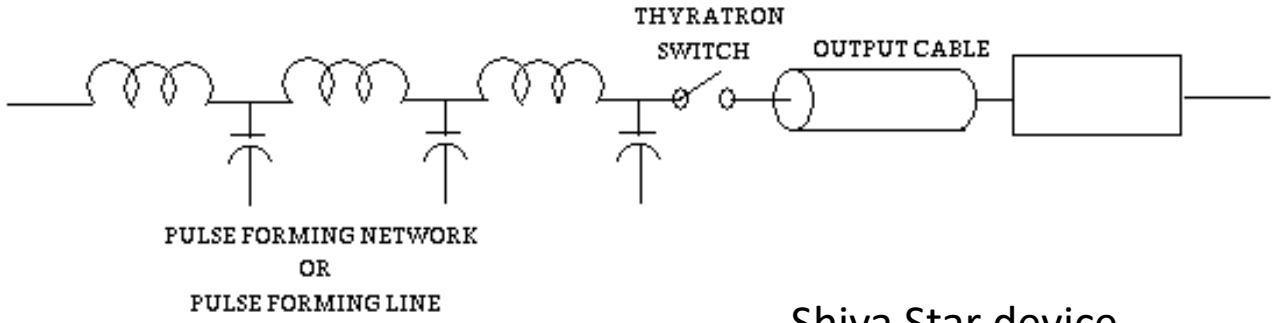




662 A_{DC} + 400 $A_{pk\text{-}pk}$ (50 Hz AC)

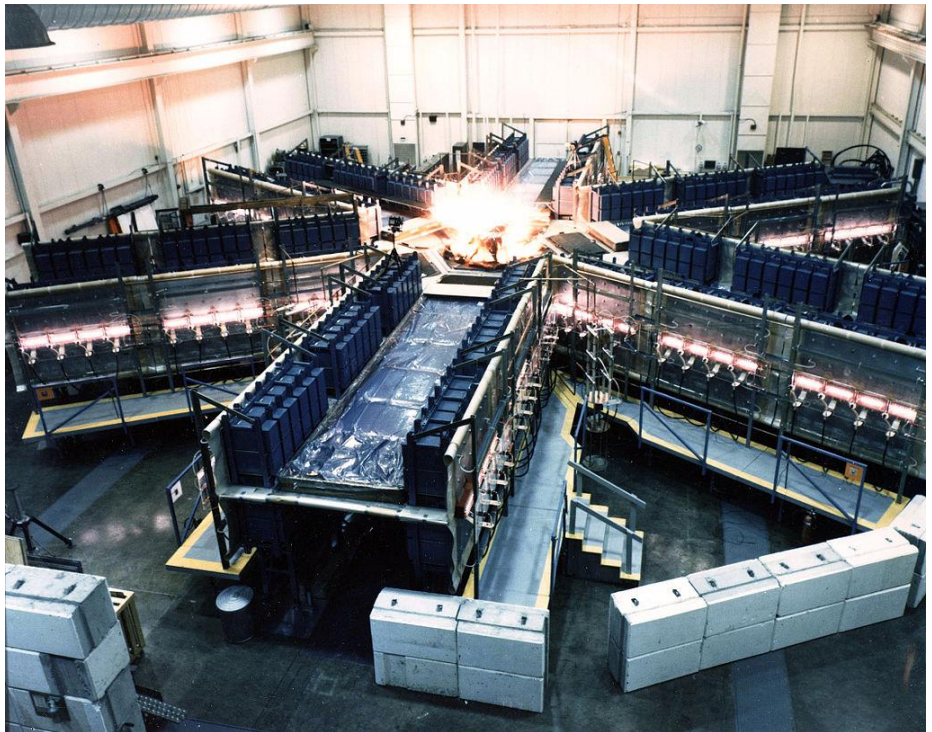
Pulse Forming Networks

Short pulses
Up to a few 1 µs



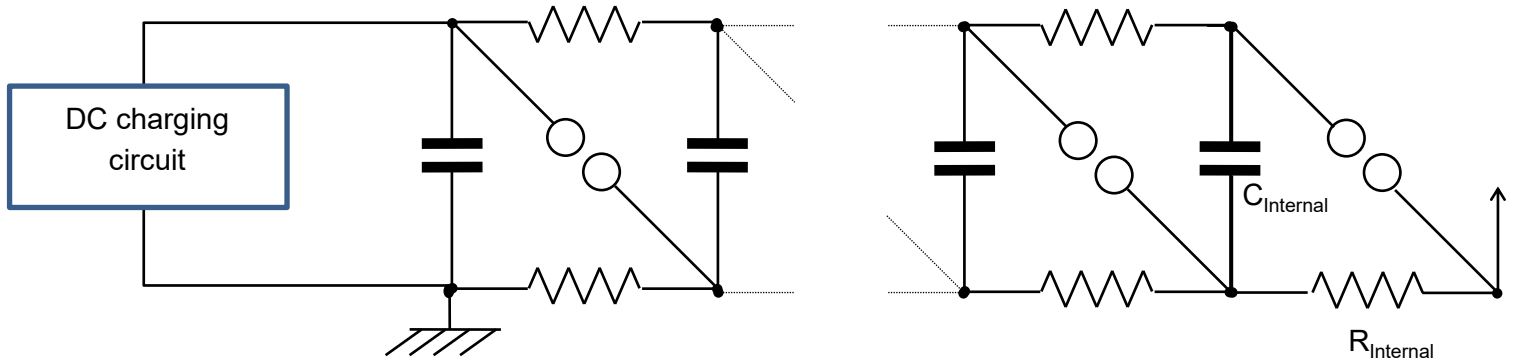
ISIS Extraction Kicker systems
500 ns 40 kV 5kA

Shiva Star device
1 µs pulses 120 kV and 6 MA



Marx Generators

Longer pulses
Up to a few 1 ms
and higher voltages

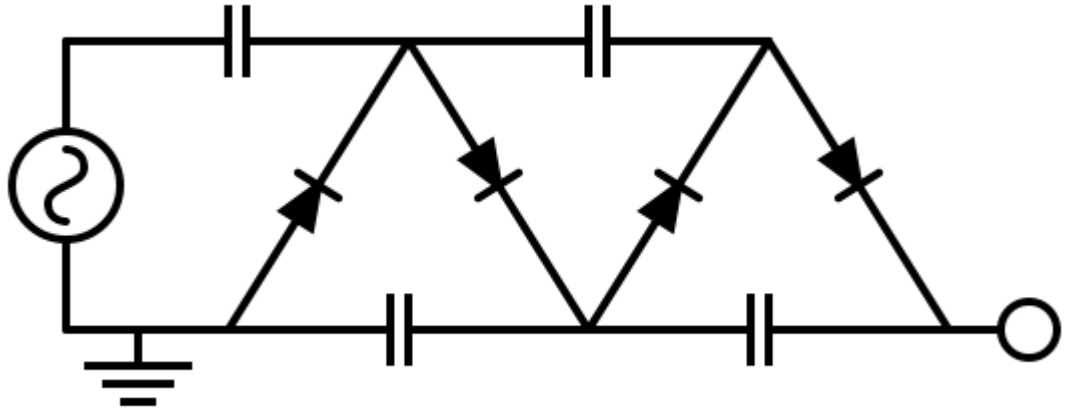


n stages charged in parallel
added in series by spark gaps

Very high pulsed voltages up to 20 MV

HV DC (mA)

Cockcroft Walton Voltage Multipliers

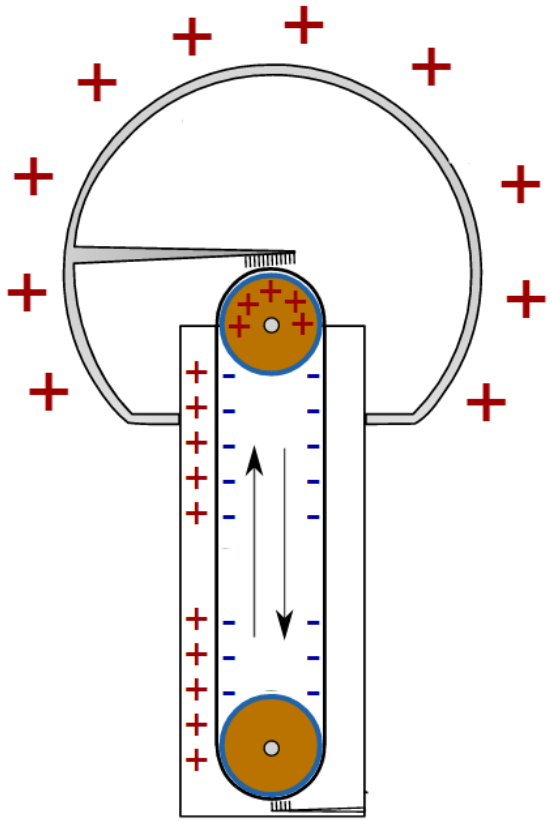


High Voltage DC

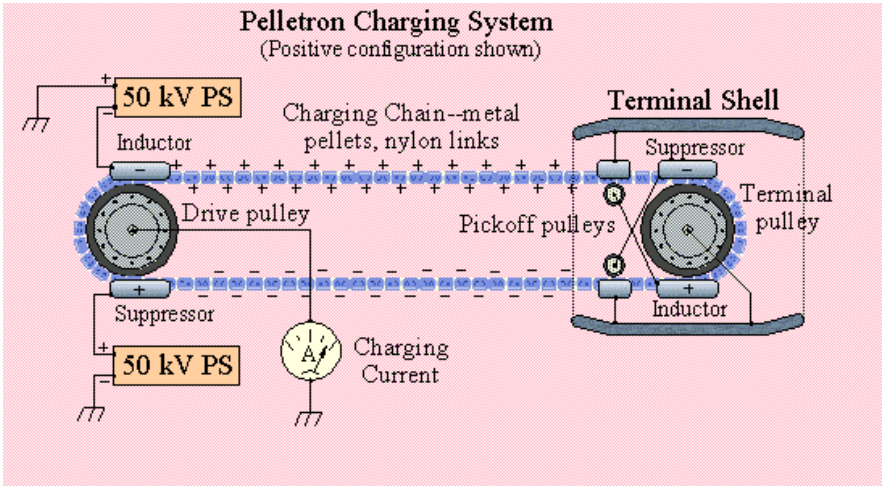
Old ISIS 665 kV preinjector

Vandergraph, Pelletron

HV DC (mA)



Daresbury 20 MV Vandergraph



Step-up transformer diode rectifier

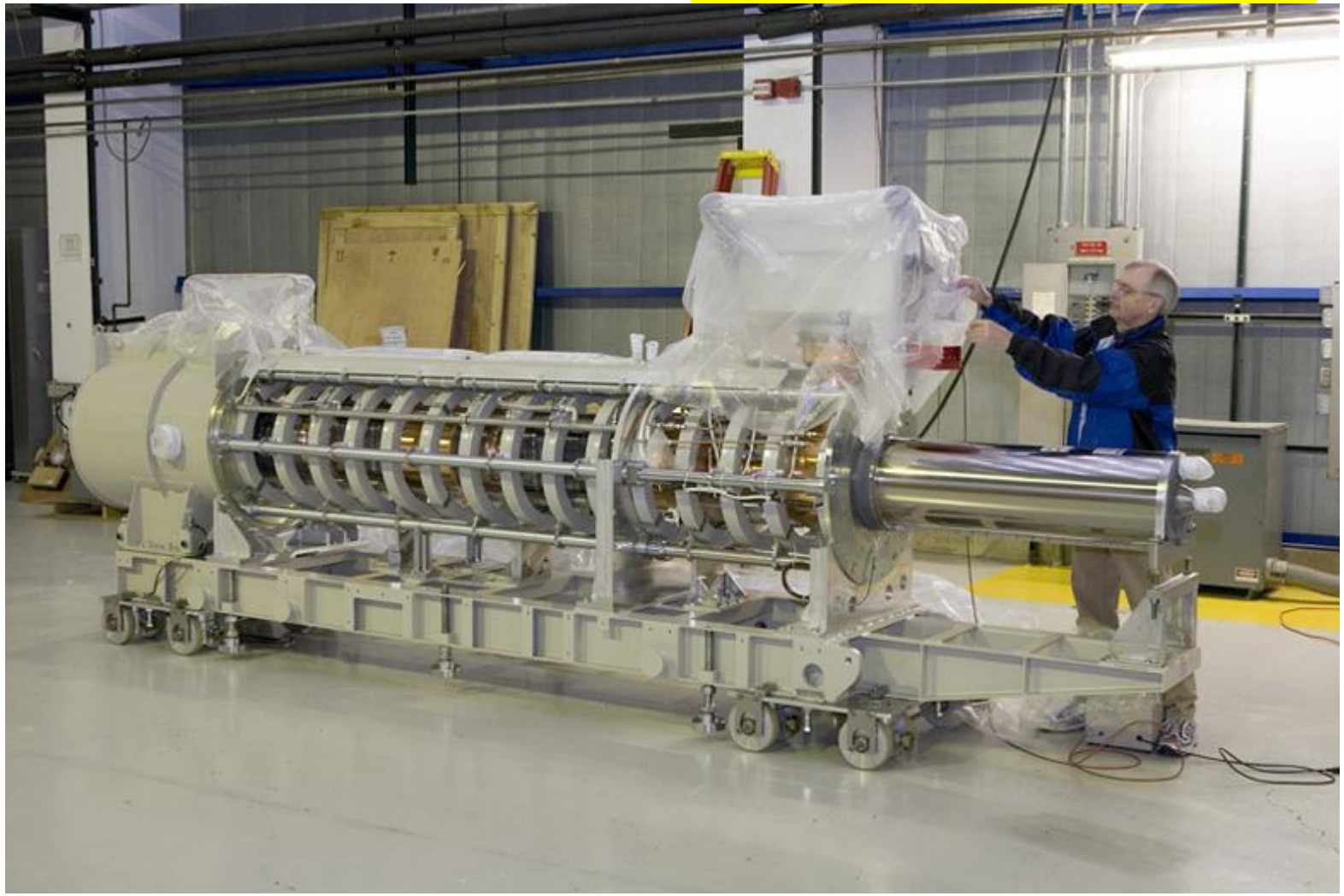
HV DC (A)

ITER NBI

1 MV 60 A

RF Klystrons

10 MW 100-1000 MHz



Power Electronics

SOLID STATE switches and amplifiers:

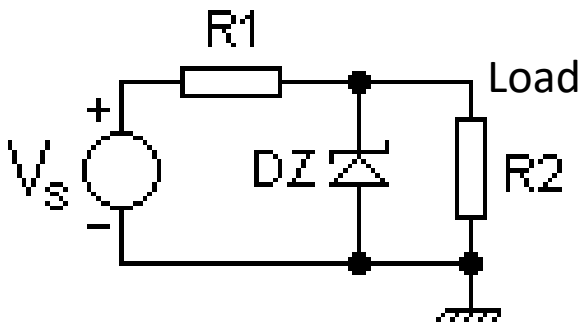
- Diodes, Zener etc.
- Transistors, Thyristors, IGBT, GTO, etc.

ELECTRON TUBES switches and amplifiers :

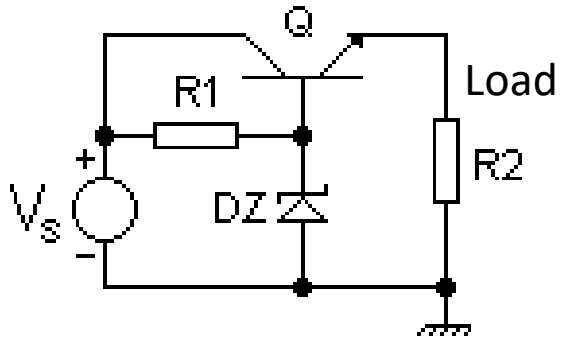
- Thyratron
- Tetrode
- Klystron, Magnetron, Gyrotron etc.

Linear vs Switched

Shunt

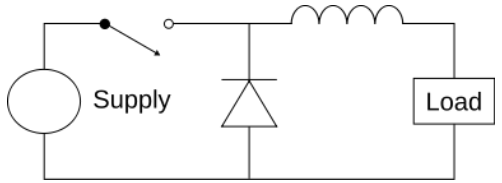


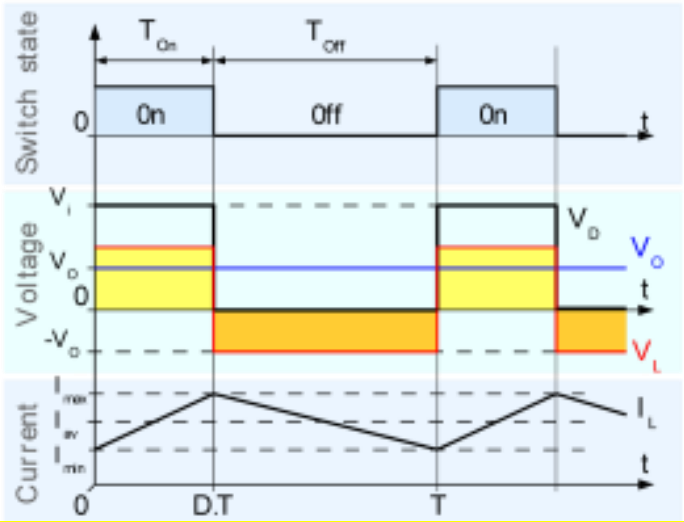
Series



Wasteful vs Noisy
Quiet vs Efficient
Heavy vs Light

Buck Converter

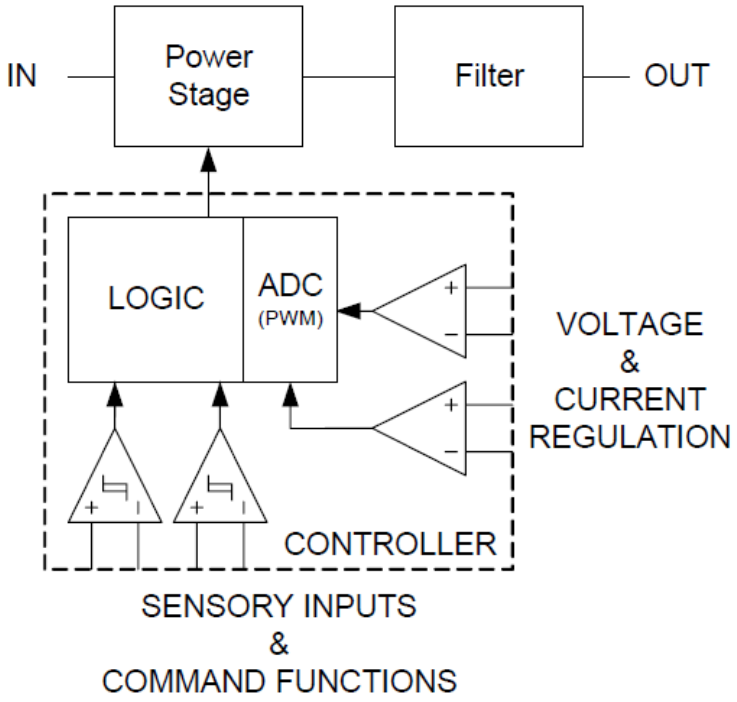




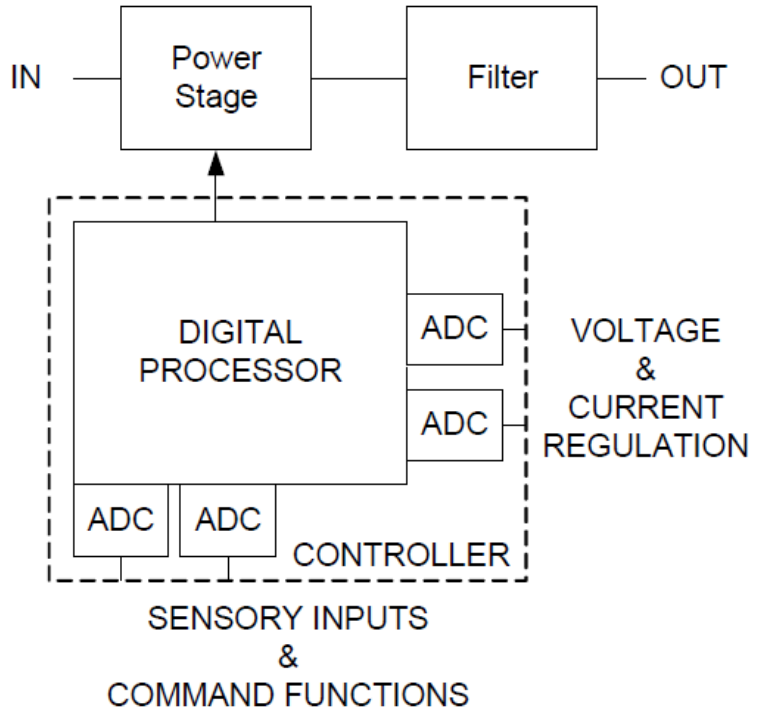
Duty cycle controls the average load voltage and current

Many other types of switched mode PS
Boost, Buck-boost, Split-pi, Ćuk, SEPIC, Zeta, Switched capacitor, Flyback, Ringing choke converter, Half-forward, Forward, Resonant forward, Push-pull, Half-bridge, Full-bridge, Resonant, zero voltage switched

Digital Power Supply?



traditional switched mode



digital

High Voltage Power Supply Manufacturers

SIEMENS

GAMMA

TDK-Lambda

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

  $\frac{1}{2}CV^2 = 0.5 \times 1\ \mu F \times 30\ kV = 450\ J$

- X-rays

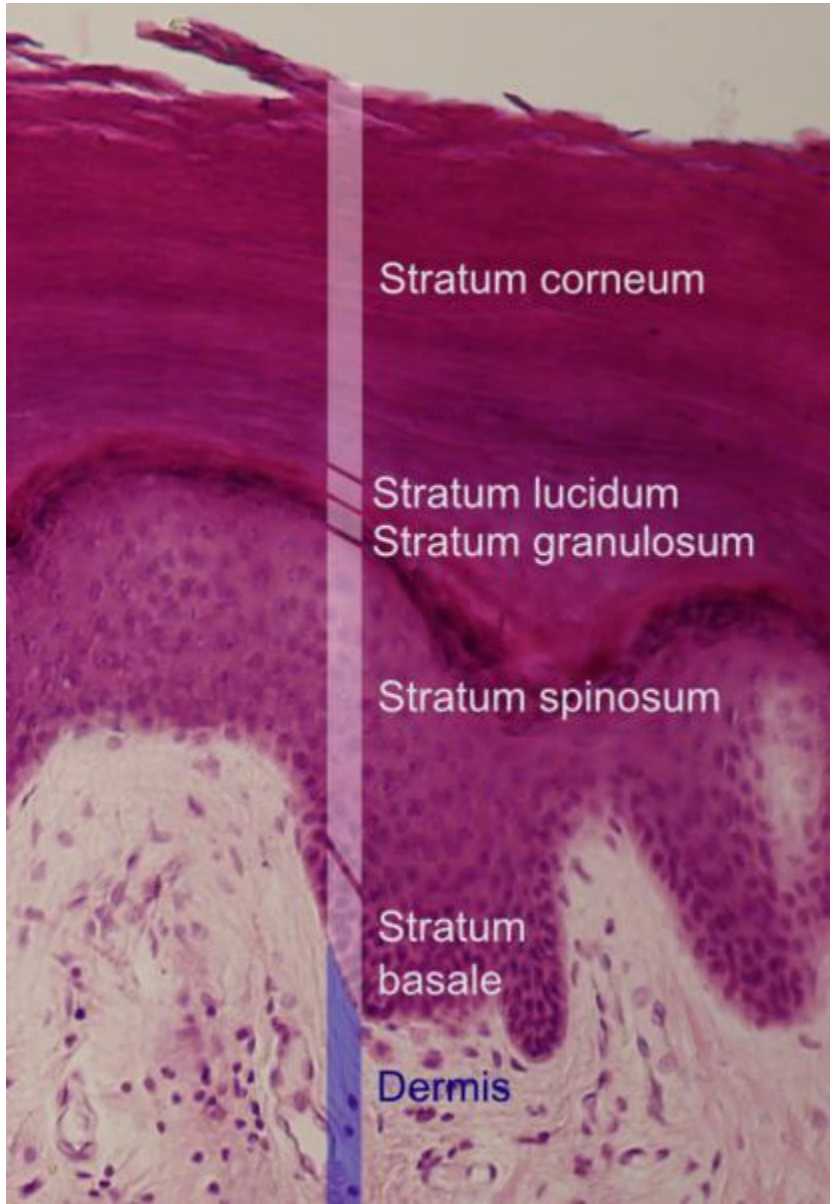
Electric Shocks

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



Functional Safety

IEC 61508

"Don't do anything stupid"

The good ol' days

"Prove how safe it is"

Now

Functional Safety

IEC 61508

- System analysis
- Safety Integrity Levels (SIL) ratings
- Failure mode analysis
- Inspection and maintenance regimes
- Documentation

“Prove how safe it is”

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.

HV Safety Philosophy

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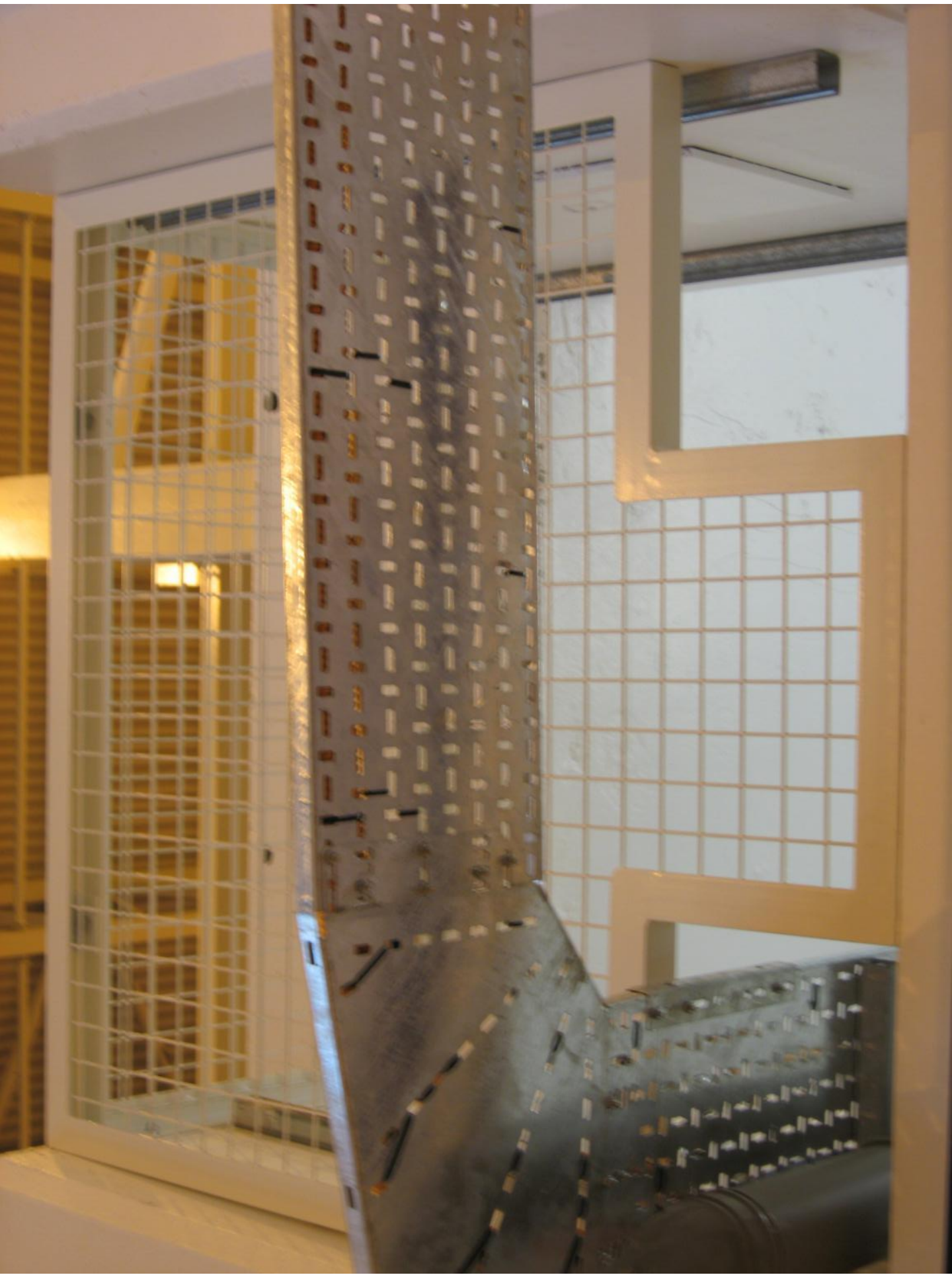
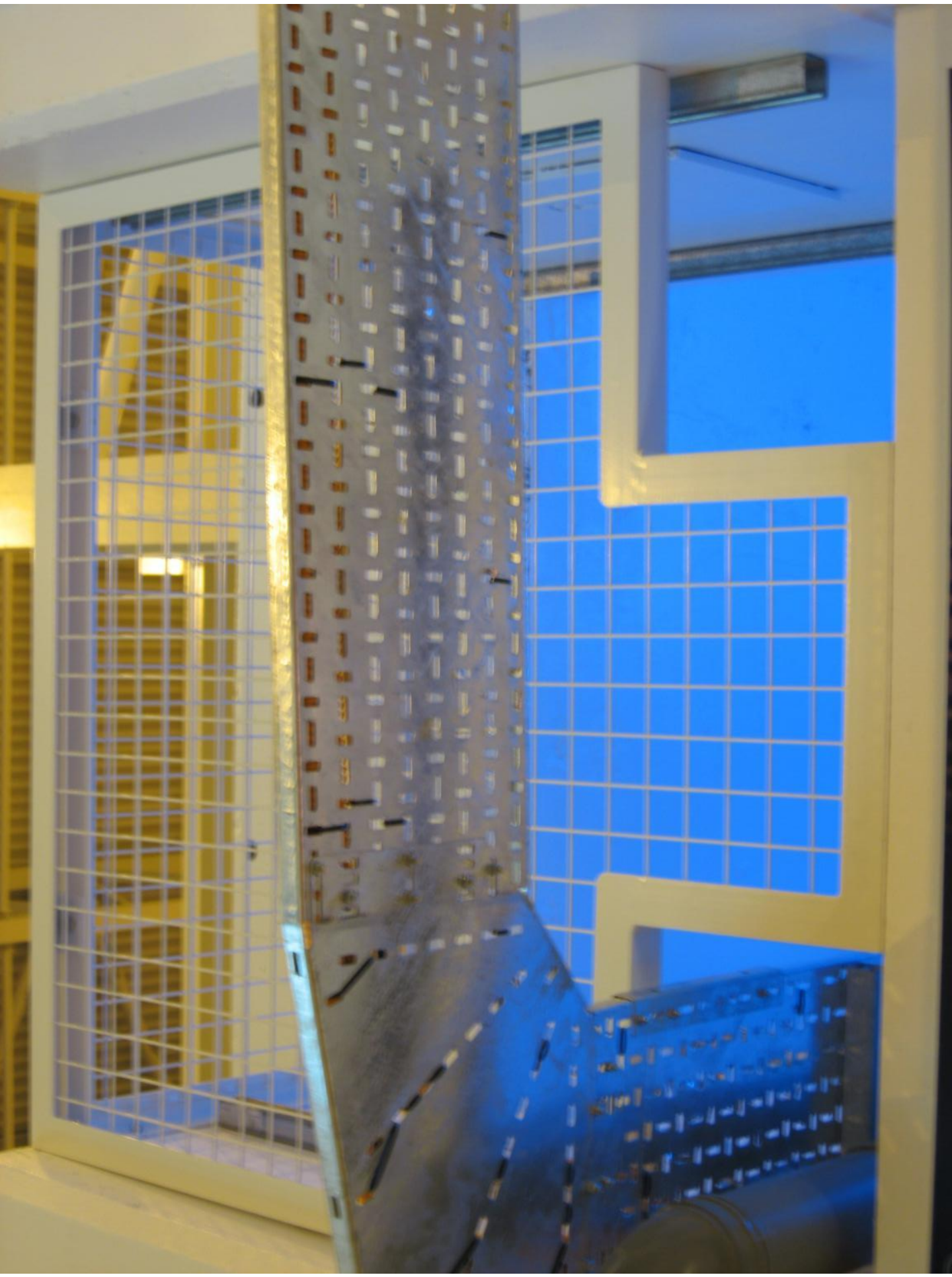
SEARCH

www.fortressinte





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

BIASO3

SONIAC VAULT
2314210

HV Safety Philosophy

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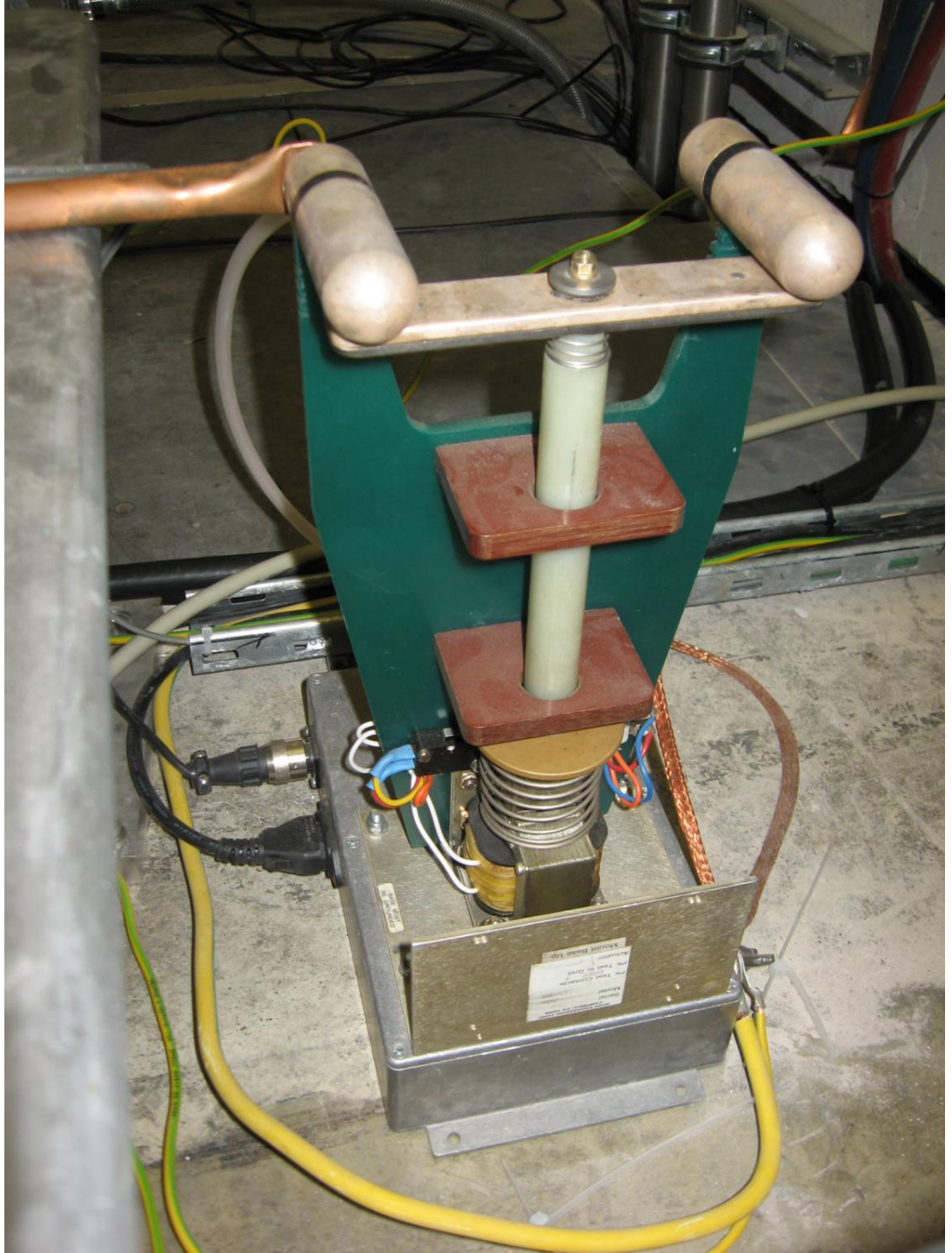
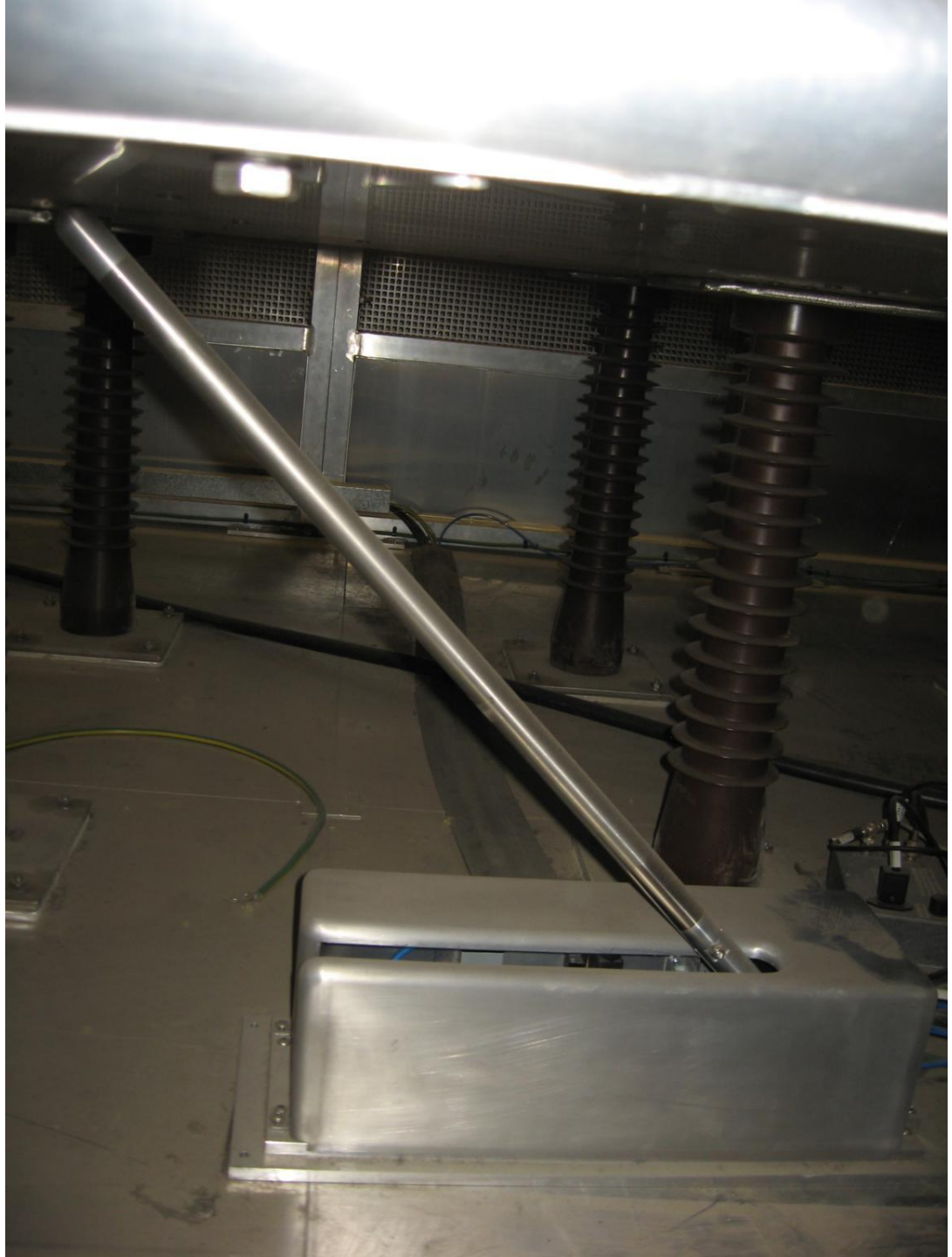
CS1

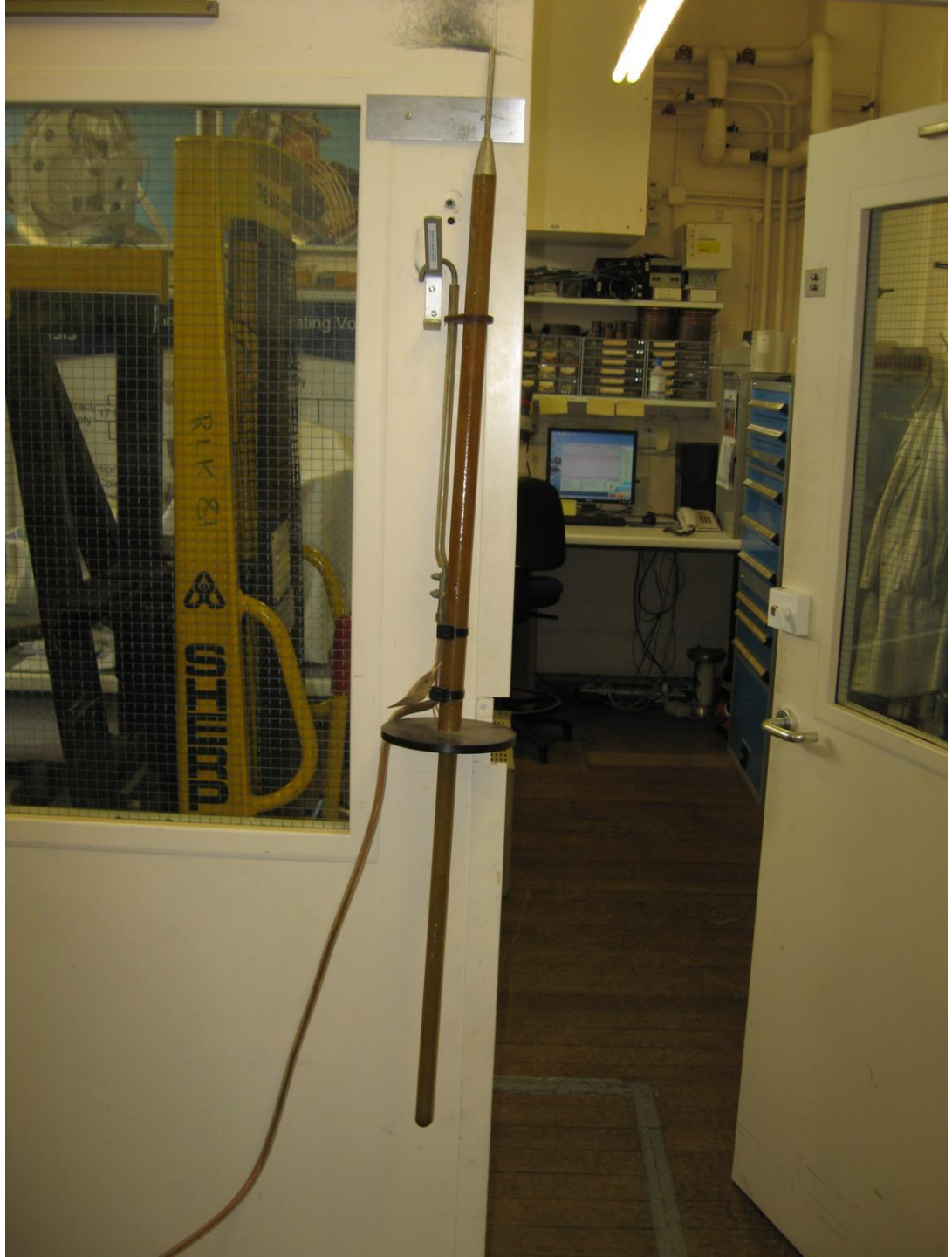
Automatic Earthing System



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
Questions?