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 Saftey

Uses of High Voltages in Ion Sources

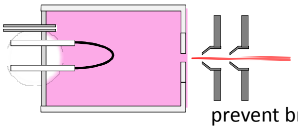
- Extracting beams (up to 50 kV)
- Accelerating beams (up to 3000 kV)
- Initiating discharges / pre-ionising gases (up to 20 kV)
- Focusing and deflecting beams (up to 50 kV)
- Suppressing unwanted particles (up to 5 kV)

Ion sources are particularly challenging for HV design

High temperatures
Explosive gasses (e.g. Hydrogen)
Other contaminants (e.g. Cs)
Magnetic fields
Compact design
Large amounts of charge carriers
Stray beams: electrons and ions

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
  - etc...

Electric Field

- Potential gradient, electric field strength, electric field intensity, stress, E
- 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:

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

$$\nabla \cdot \mathbf{B} = 0 \qquad \mathbf{D} = \varepsilon \mathbf{E}$$

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

or

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

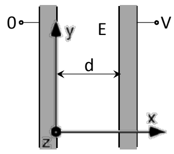
if $\rho = 0$:

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

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

Infinite parallel plates:



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

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

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

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

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

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

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

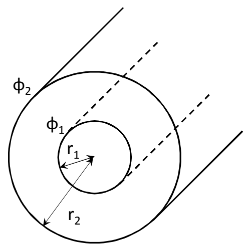
At $x = 0,\ \phi = 0$ and at $x = d, \phi = V$

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

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

Similarly....

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



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

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

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

Fine for simple geometries...

Finding Electric Field Distributions

Teledeltos paper

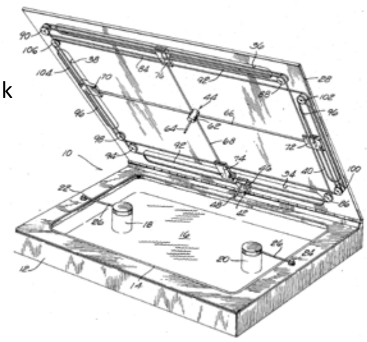
Silver Paint

Power supply, voltmeter and probe

Manually find equipotentials

Finding Electric Field Distributions

Automated Electrolytic tank

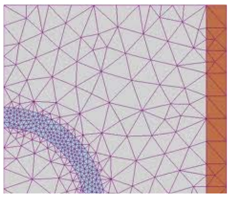


Thankfully we have Computers

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

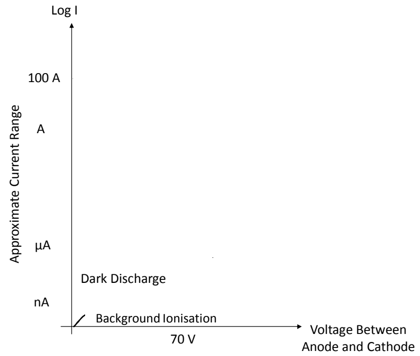
Mostly 2D
Poor geometry input
Poor meshing
Poor post processing
No/poor support

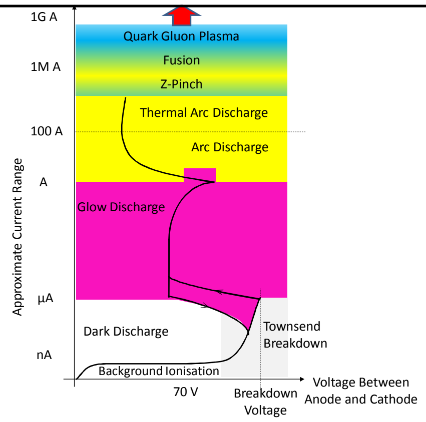
If you want a free 2D solver:
LAACG
Poisson Superfish

Commercial 3D Modelling Software

ANSYS
COBHAM Vector Fields software for electromagnetic design
Opera
CST
Autodesk ALGOR
COMSOL
MAGSOFT CORPORATION
SIMION®
Field Precision

Electrical Discharges





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

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- Global break down can only occur when a highly conductive channel is formed between the two
- 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

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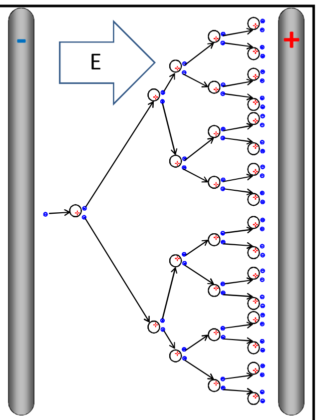
Avalanche

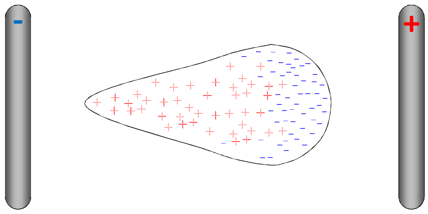
John Townsend
"Townsend discharge"
1897

$$dn_x = n_x \alpha dx$$

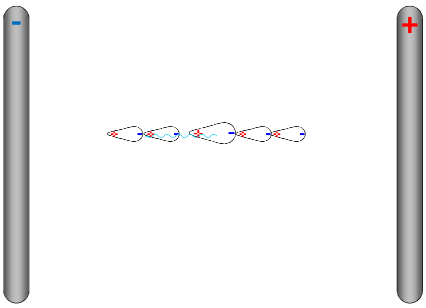
$$n_x = n_0 e^{\alpha x}$$



Avalanche



Streamer



Townsend Secondary Ionisation Coefficient

John Townsend
"Townsend discharge"
1897

$$dn_x = n_x \alpha dx$$

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

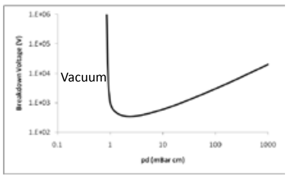
$$\gamma = \gamma_{ion} + \gamma_p + \gamma_m$$

Self sustaining discharge resulting in breakdown

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

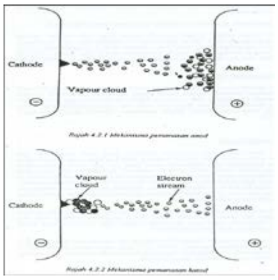
Paschen Curve

Friedrich Paschen 1889



Distance in reality is limited by field emission

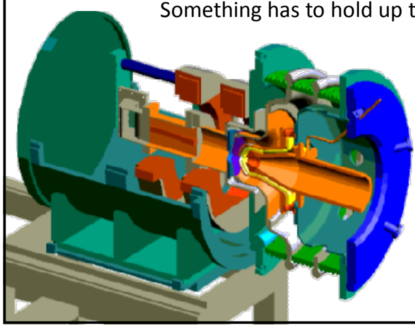
Vacuum Breakdown



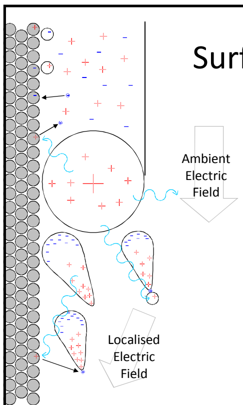
Extraction conditioning
Kilpatrick

Insulators

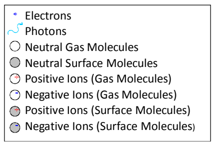
Something has to hold up the electrodes



Surface Breakdown

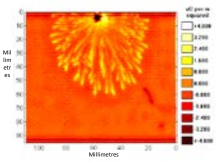


Insulator surfaces are the weakest part of the insulation system



Surface Charging

Dust Figure



Charge Distribution

Applied Impulse:	**+36.0kVp**	Ipeak:	**+0.31A**
Time of corona:	**1.660µs**	Injected Q:	**+8.8nC**
Instantaneous Voltage:	**+24.9kV**	Net Surface Charge:	**+0.83nC**
Initial Velocity: **$4.6\times10^5ms^{-1}$**		Total Positive:	**+1.46nC**
Distance Travelled:	**61mm**	Total Negative: **-0.63nC**	

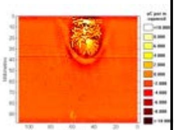
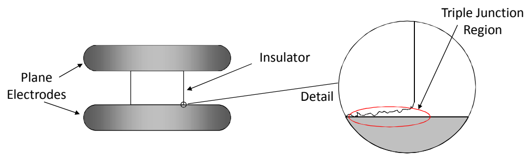
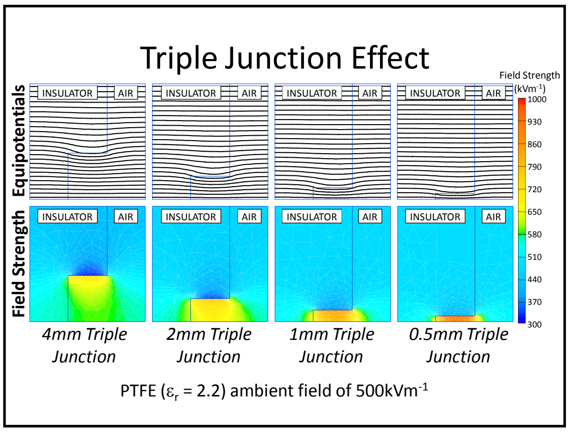
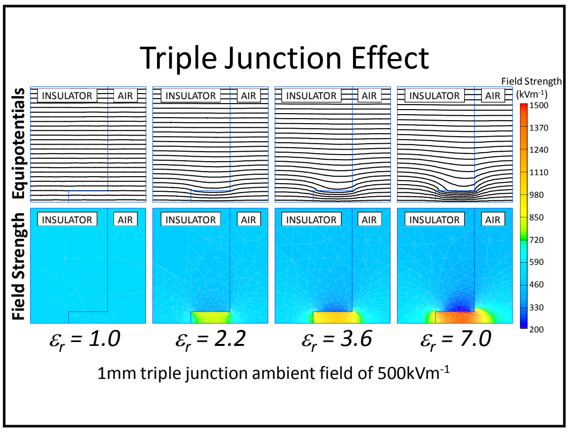


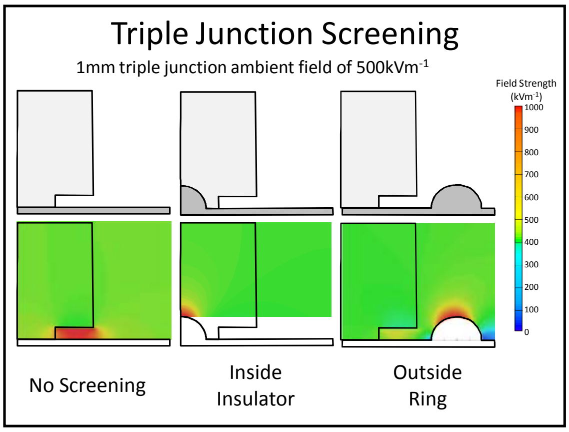
Figure 3.7.4: Surface Charge Deposited after a single −70.6kVp impulse applied to the rod (Surface Initially Neutralised)

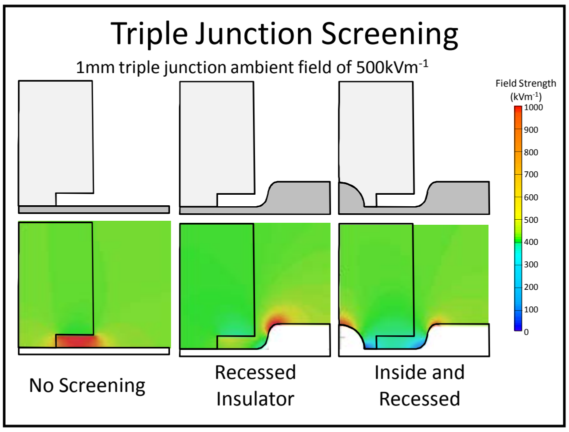
Triple junctions always exist at some scale

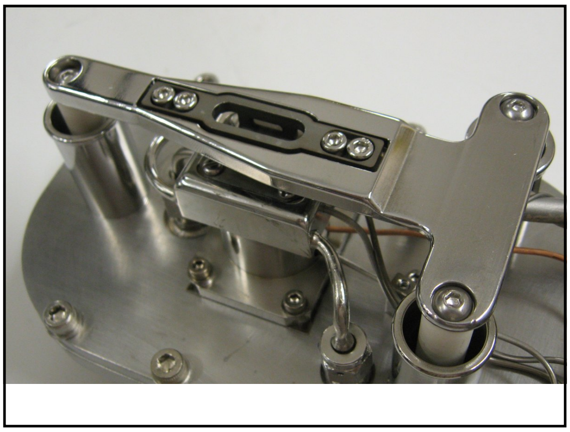


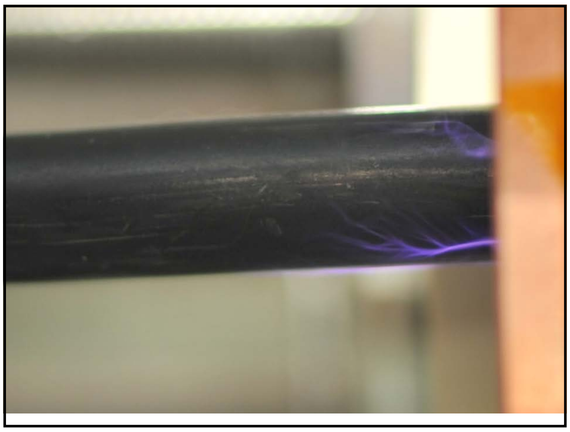

Triple Junction Effect
Equipotentials
Field Strength
INSULATOR
AIR
Field Strength (kVm-1)
1000
930
860
790
720
650
580
510
440
370
300
4mm Triple Junction
2mm Triple Junction
1mm Triple Junction
0.5mm Triple Junction
PTFE (εr = 2.2) ambient field of 500kVm-1

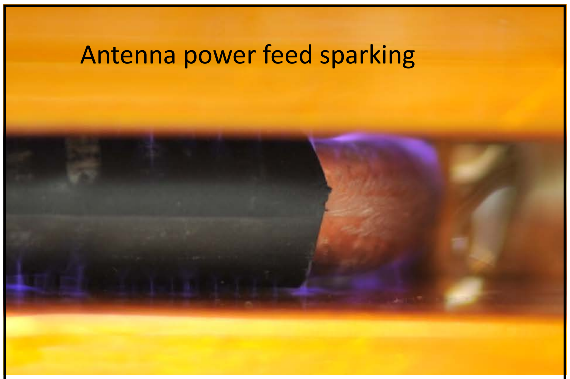

Triple Junction Effect
Equipotentials
Field Strength
INSULATOR
AIR
Field Strength (kVm-1)
1500
1370
1240
1110
980
850
720
590
460
330
200
εr = 1.0
εr = 2.2
εr = 3.6
εr = 7.0
1mm triple junction ambient field of 500kVm-1

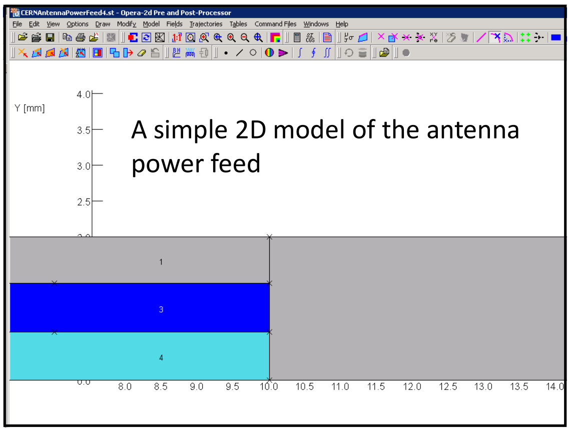

Triple Junction Screening
1mm triple junction ambient field of 500kVm-1
Field Strength (kVm-1)
1000
900
800
700
600
500
400
300
200
100
0
No Screening
Inside Insulator
Outside Ring

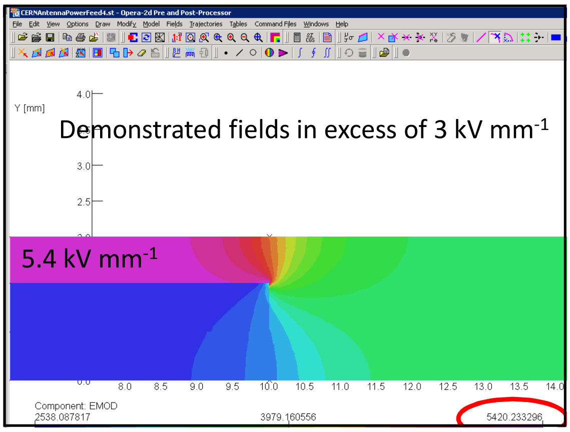

Triple Junction Screening
1mm triple junction ambient field of 500kVm-1
Field Strength (kVm-1)
1000
900
800
700
600
500
400
300
200
100
0
No Screening
Recessed Insulator
Inside and Recessed



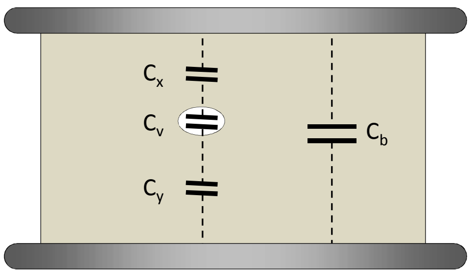








Partial Discharges

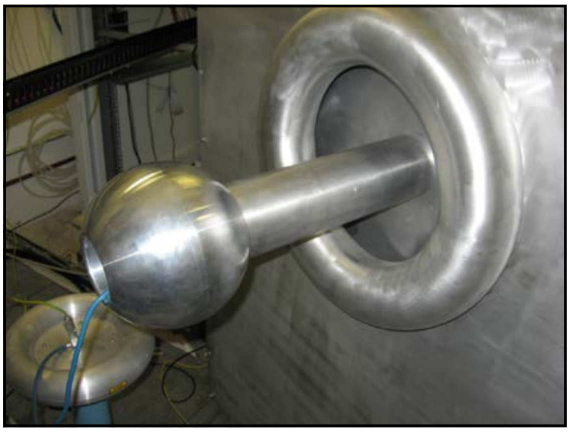


Insulator Materials

Corona

Electrode Design

Minimise Electric Field
Shield any sharp points

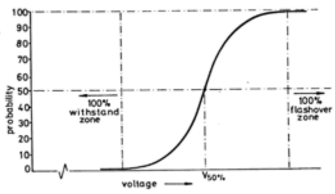


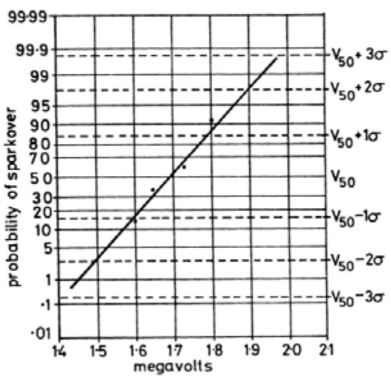
Breakdown strength of Air

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

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.





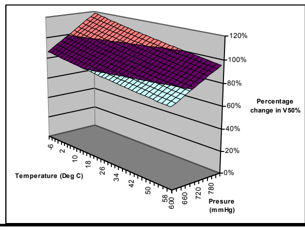
Environmental conditions

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

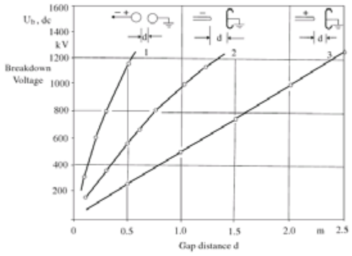
$$\frac{0.386 \times P}{273 + t}$$

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

Humidity can also affect break down voltage



Polarity is important in Non Uniform Gaps



	Gap.		[illegible]
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 &lateral)		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

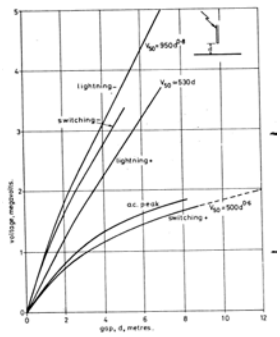


Fig. 7 Comparative breakdown voltage characteristics of a rod-plane gap in air.

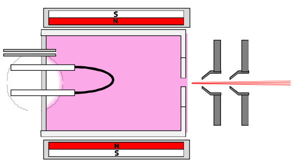
Type of Applied Voltage is Important

Additional complications

- Magnetic Fields
- Xrays
- Space charge
- Insulator surface charge

High Voltage Design

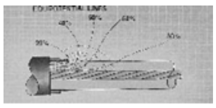
High voltage platform or internal isolation

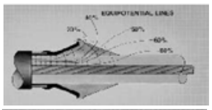


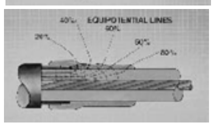
Pros and cons

Cables and Terminations

Correct termination of high voltage cables is essential



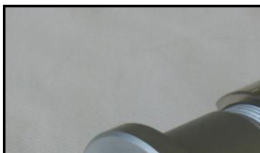


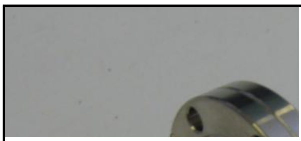


Connectors or Bushings?

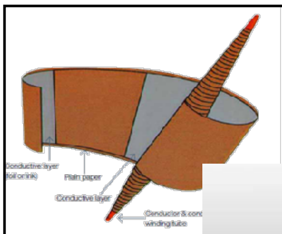
Depends on...

- Application
- Maintenance
- Permanence





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...

Clean lab conditions!

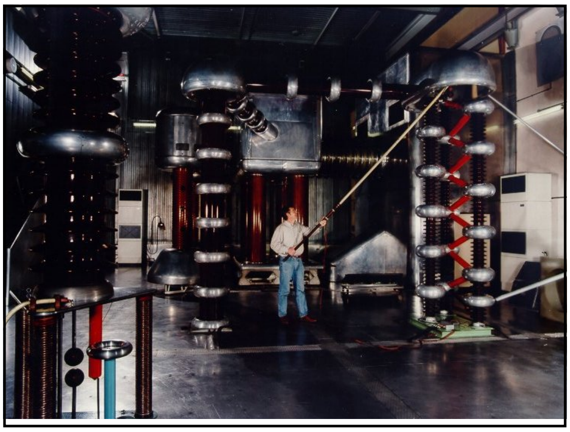
Water and home made insulators don’t mix

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

Power to the Platform

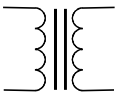
How to get power to the equipment on the HV platform?

- Motor alternator set
- Isolating transformer



Solid Insulation Isolation Transformer

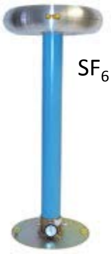
1:1



Oil Filled Isolation Transformer

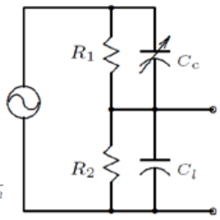
Pro: Compact design
Con: Bund required

Voltage Dividers



SF_6 Filled

Compensated



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

If $R_1C_c = R_2C_l$ $\quad K = \frac{R_2}{R_1 + R_2}$

Insulation Test Equipment

Current limited test of insulation

Power Supply Technologies

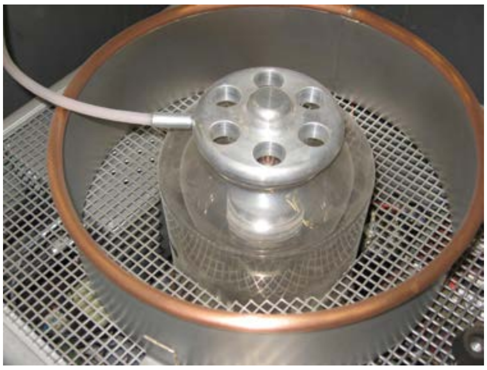
- Semiconductors: Thyristor, IGBT, GTO
- Tube- tetrode
- PFN
- Cascade rectifier (Greinacher/ Cockcroft–Walton multiplier)
- Vandergraph, peloton
- Linear (Usually front end only)
- Switched mode-transformer -HV Diode and Capacitor

High Voltage Power Supply Manufacturers

GLASSMAN HIGH VOLTAGE INC.
SIEMENS
DANFYSIK
Heinzinger
ETPS Limited
ULTRAVOLT
Genvolt
DIVERSIFIED TECHNOLOGIES, INC.
fug
HiTek Power
ppm POWER
BRUKER
Jema
AHV
Matsusada Precision
KEPCO
EMCO
APPLIED KILOVOLTS
Spellman
GAMMA
TDK
TDK-Lambda
a.t.e. systems

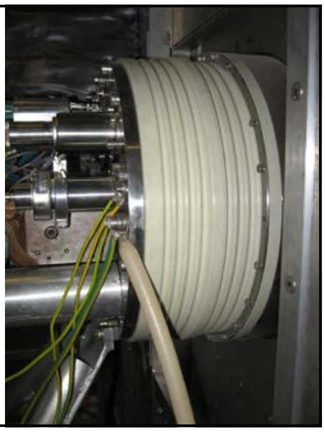
Custom Built Power Supplies

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



Earthing

High voltage platform
"Local earth"



Safety

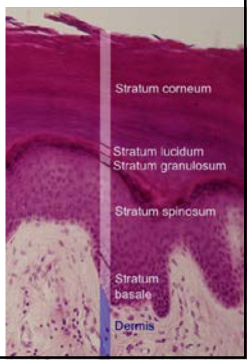
- Electric Shocks can kill
- Stored energy in capacitors

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

Electric Shocks

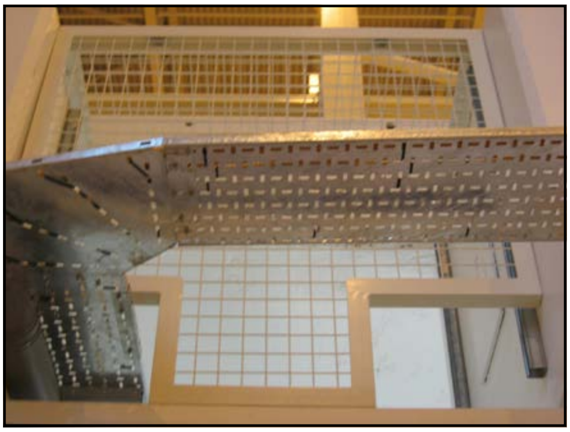
Hand to hand resistance
100 kΩ dry/thick skin
1 kΩ wet/broken skin

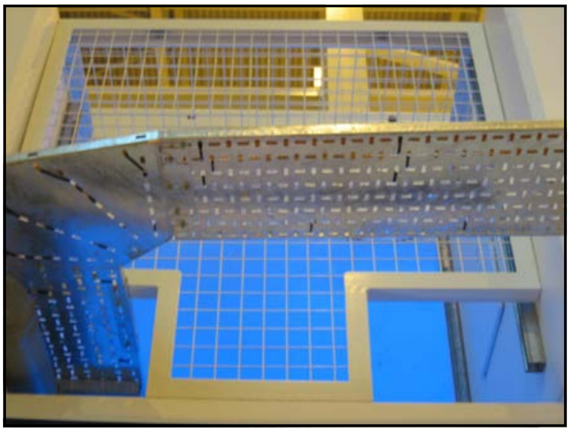
- The stratum corneum breaks down 450–600 V leaving 500 Ω
- You can feel 5 mA
- 60 mA can fibrillate the heart



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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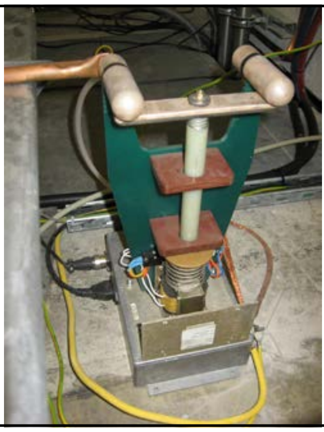
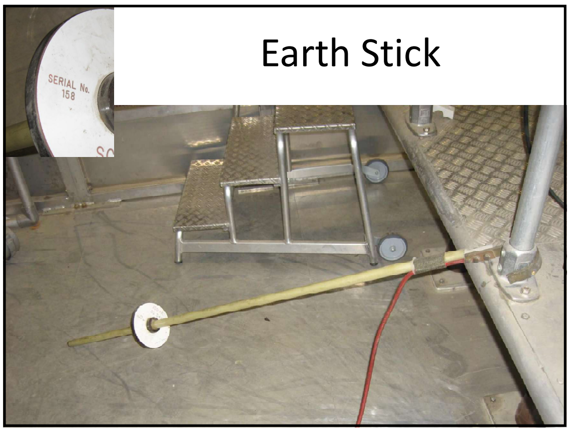
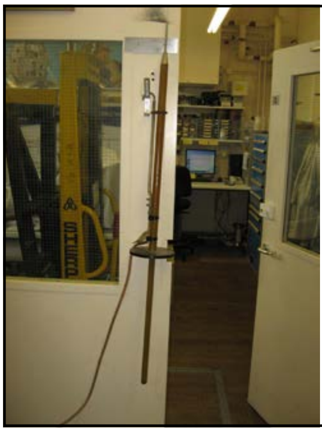
Automatic Earthing System



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...

Let that be a lesson!

Thank you for listening