Electrical Insulation for Magnets

dielectrics, design and construction

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Outline

- **E-Field basics**
  - Formulas
- **Dielectrics and Breakdown mechanisms**
  - Gas (and vacuum)
  - Liquid
  - Solid
- **Insulation systems for Magnets**
  - Composites, manufacturing
  - Magnet wire insulation
  - Inorganic insulation
- **High Voltage testing**
- **Extra**

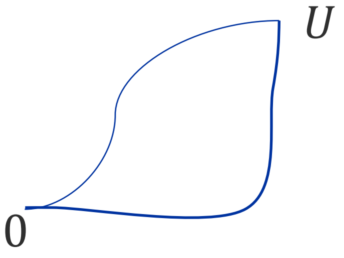
E-Field basics

Electric Field and Potential

- High Voltage Engineering deals with electrostatic fields which have the advantage to simplify the equations. **Electrostatic fields** are generated only by (static) **electric charges q**

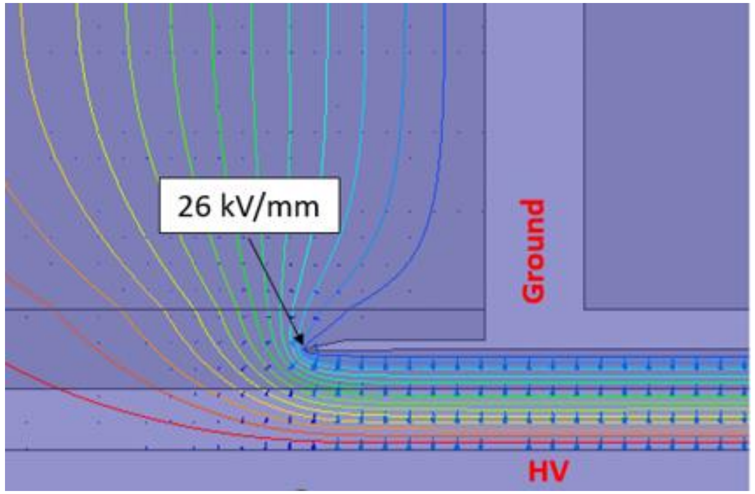
- Electrostatic fields are **conservative fields**

$$\nabla \times \mathbf{E} = -\cancel{\frac{\partial \mathbf{B}}{\partial t}} = 0 \qquad \oint \boldsymbol{E}\,\mathrm{d}\boldsymbol{l} = 0$$



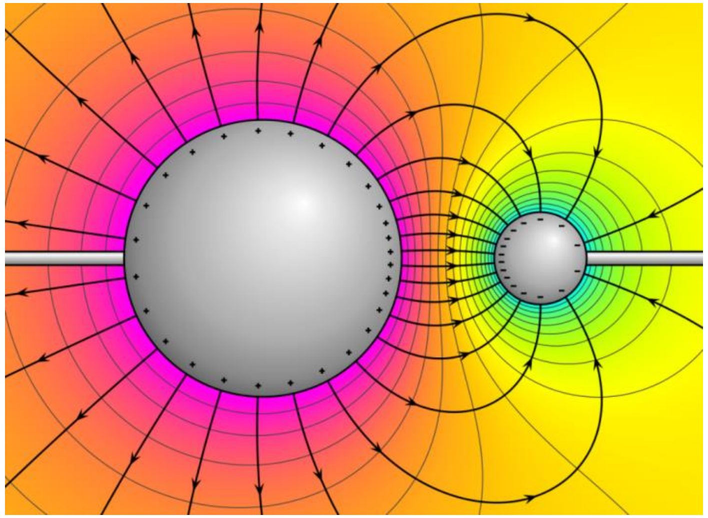
$$\boxed{\int_1 \boldsymbol{E}\,\mathrm{d}\boldsymbol{l} = \int_2 \boldsymbol{E}\,\mathrm{d}\boldsymbol{l} = U}$$

- Electric Field is expressed as the gradient of a scalar, the **electrostatic potential**



$$\mathbf{E} = -\nabla \mathbf{U}$$

The highest is the “density” of equipotential lines, the highest is E



- Finally, the Gauss Law

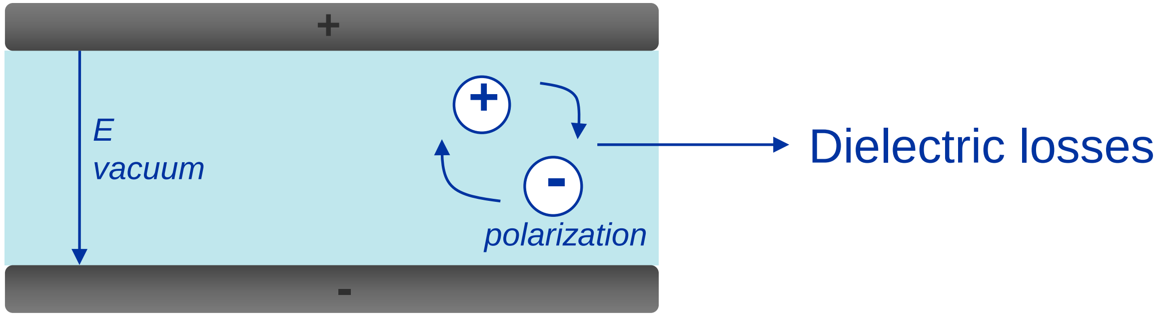
$$\nabla \cdot \mathbf{E} = \frac{\rho_{\text{free}}}{\varepsilon_0} \qquad \oiint_S \mathbf{E} \cdot \mathrm{d}\mathbf{A} = \frac{Q_{\text{free}}}{\varepsilon_0}$$

D-Field and Permittivity

In presence of matter…

$$\boldsymbol{D} = \varepsilon_0 \boldsymbol{E} + \boldsymbol{P}$$

The **Electric Polarization P**, is the induced field due to the dipoles in the material. It's the density of dipole moments in the material.



The **Displacement Field D** accounts for the polarization effect within the dielectric materials.

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

With ε = ε0εr

The permittivity is a physical property of the dielectrics. If the material is linear (susceptibility is not a function E-Field strength) and isotropic (E-field parallel to D-field) ε is simply a scalar quantity.

ε0 = 8.854x10-12 F/m is the "dielectric constant of free space"

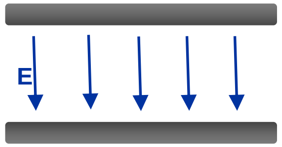
εr is the dielectric constant or permittivity of the material

Electric Field Calculations

For simple configurations, the E field can be calculated exactly:

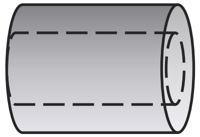
- Parallel plates

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



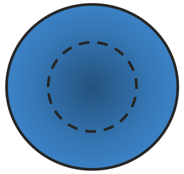
- Concentric cylinders

$$\boxed{E = \frac{V}{x^2\left(\frac{1}{r} - \frac{1}{R}\right)}}$$



- Concentric spheres

$$\boxed{E = \frac{V}{x\ln\left(\frac{R}{r}\right)}}$$

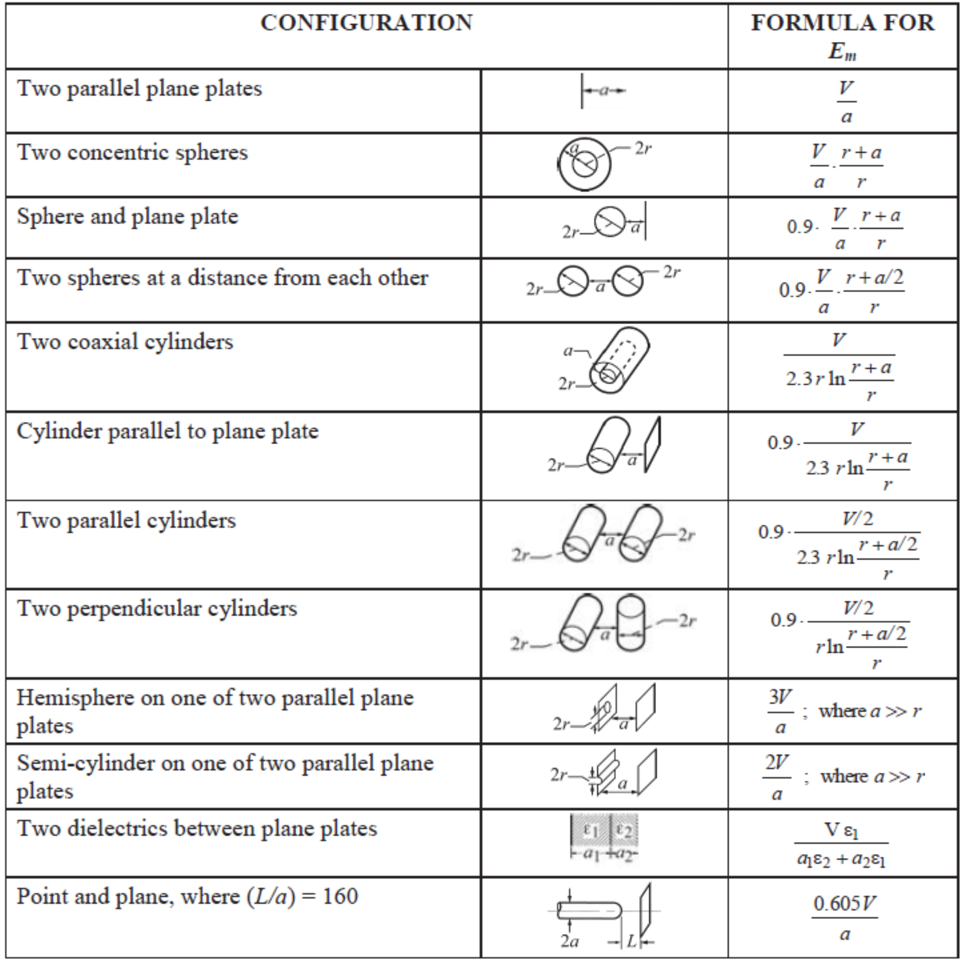


Other basic configurations are calculated by **analytical methods** (e.g. conformal mapping) and empirical formulas. **Tables and empirical formula** provides maximum electric fields which are often enough for quick design assessments.

Numerical methods (e.g. FEM) are used for design optimization of more complex and multidielectric constructions.

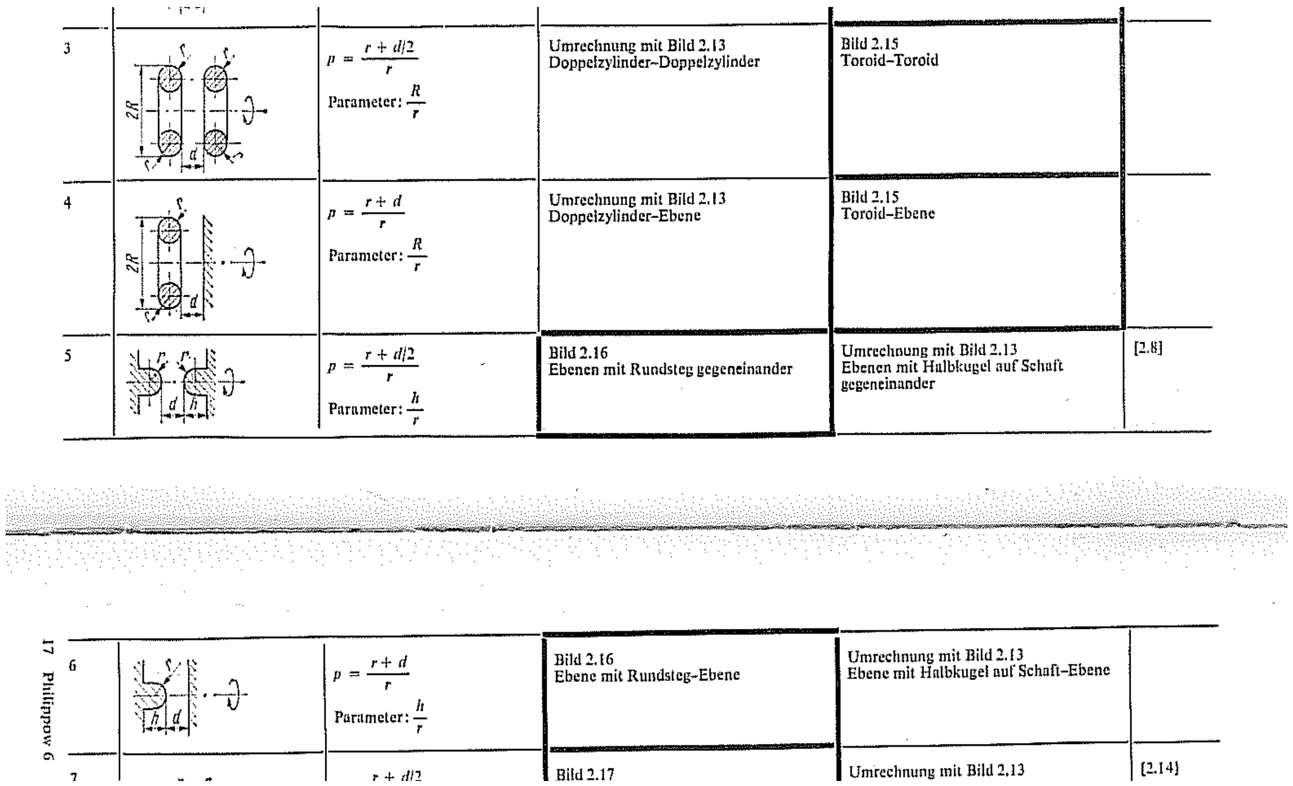
Maximum Field Formulas

Maximum Field Strength E_m



CONFIGURATION		FORMULA FOR E_m
Two parallel plane plates		$\frac{V}{a}$
Two concentric spheres		$\frac{V}{a} \cdot \frac{r+a}{r}$
Sphere and plane plate		$0.9 \cdot \frac{V}{a} \cdot \frac{r+a}{r}$
Two spheres at a distance from each other		$0.9 \cdot \frac{V}{a} \cdot \frac{r+a/2}{r}$
Two coaxial cylinders		$\frac{V}{2.3\, r \ln \frac{r+a}{r}}$
Cylinder parallel to plane plate		$0.9 \cdot \frac{V}{2.3\, r \ln \frac{r+a}{r}}$
Two parallel cylinders		$0.9 \cdot \frac{V/2}{2.3\, r \ln \frac{r+a/2}{r}}$
Two perpendicular cylinders		$0.9 \cdot \frac{V/2}{r \ln \frac{r+a/2}{r}}$
Hemisphere on one of two parallel plane plates		$\frac{3V}{a}$; where $a >> r$
Semi-cylinder on one of two parallel plane plates		$\frac{2V}{a}$; where $a >> r$
Two dielectrics between plane plates		$\frac{V \varepsilon_1}{a_1 \varepsilon_2 + a_2 \varepsilon_1}$
Point and plane, where $(L/a) = 160$		$\frac{0.605V}{a}$

Source: NASA Technical Handbook, Spacecraft HV Paschen and Corona Design Handbook



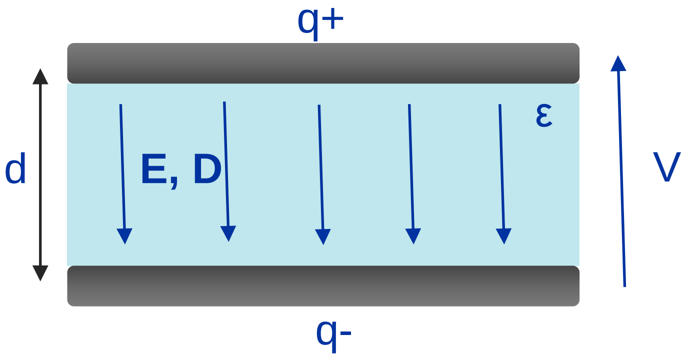
3		$p = \frac{r + d/2}{r}$ Parameter: $\frac{R}{r}$	Umrechnung mit Bild 2.13 Doppelzylinder–Doppelzylinder	Bild 2.15 Toroid–Toroid	
4		$p = \frac{r + d}{r}$ Parameter: $\frac{R}{r}$	Umrechnung mit Bild 2.13 Doppelzylinder–Ebene	Bild 2.15 Toroid–Ebene	
5		$p = \frac{r + d/2}{r}$ Parameter: $\frac{h}{r}$	Bild 2.16 Ebenen mit Rundsteg gegeneinander	Umrechnung mit Bild 2.13 Ebenen mit Halbkugel auf Schaft gegeneinander	[2.8]
6		$p = \frac{r + d}{r}$ Parameter: $\frac{h}{r}$	Bild 2.16 Ebene mit Rundsteg–Ebene	Umrechnung mit Bild 2.13 Ebene mit Halbkugel auf Schaft–Ebene	
7		$r + d/2$	Bild 2.17	Umrechnung mit Bild 2.13	[2.14]

17 Philippow 6

Source: Elektrotechnik Band 6 Systeme der Elektroenergietechnik 1

Parallel plates

$$E = \frac{V}{d}$$ [kV / mm]

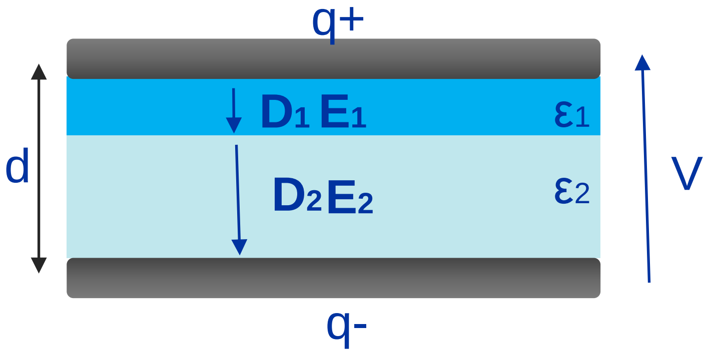


From Gauss Law and assuming free charges only at the plates:

$$D_1 A = D_2 A = q$$

$$E_1 \varepsilon_1 = E_2 \varepsilon_2 = const.$$

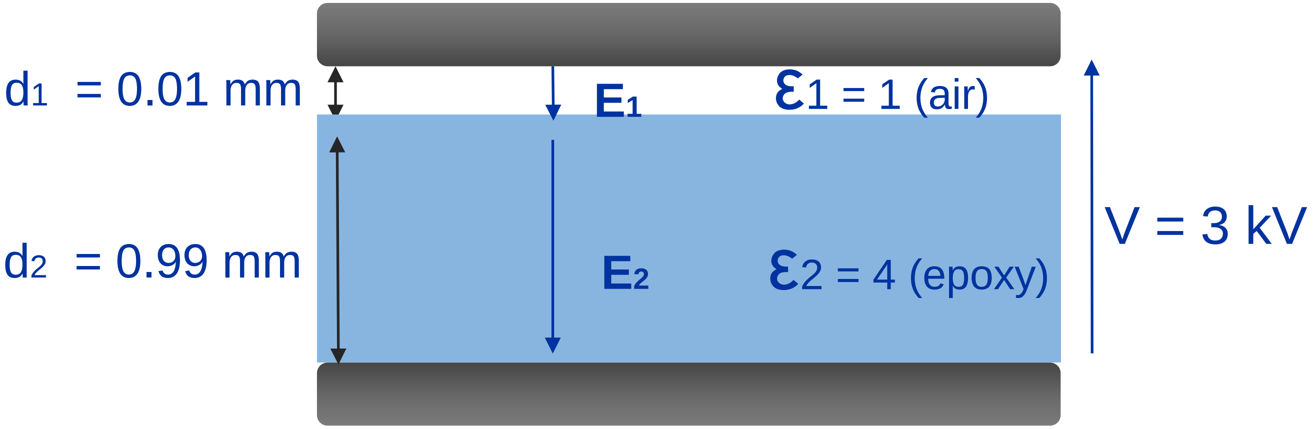
$$\boxed{\frac{E_1}{E_2} = \frac{\varepsilon_2}{\varepsilon_1}}$$



The electric field is stronger in the dielectric with lower permittivity!!!

Field enhancement

$$V = E_1 d_1 + E_2 d_2$$



Substitute E_2 with the relation in the previous slide:

$$E_1 = \frac{V}{d_1 + \frac{\varepsilon_1}{\varepsilon_2} d_2} \approx \frac{3\ kV}{1\ \frac{1}{4}\ mm} \approx 12\ kV/mm$$

$$E_2 \approx 3\ kV/mm$$

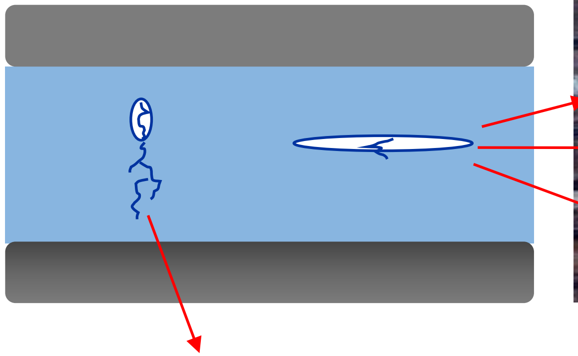
While the dielectric strength of epoxy is around 20 – 30 kV/mm the one of air is ~ 3 kV/mm. We can expect electrical discharges in the air gap

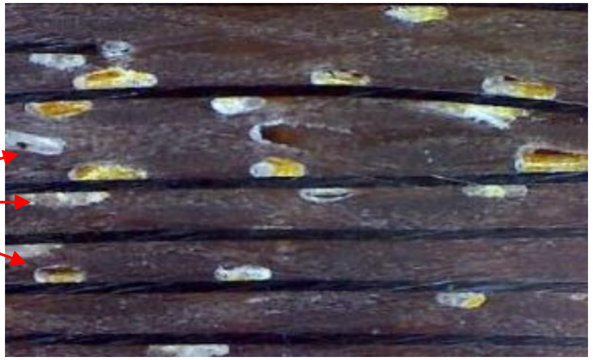
Be careful combining dielectrics with different permittivity. Solid dielectrics (ε = 2 - 10), gaseous dielectrics (ε ≈ 1), liquids (ε_water = 80)

Partial discharges

Real insulation are far from being ideal. Debonding of insulation, delamination, bubbles in liquids, voids in solids, etc. are defects that may cause **partial discharges (PD)**.

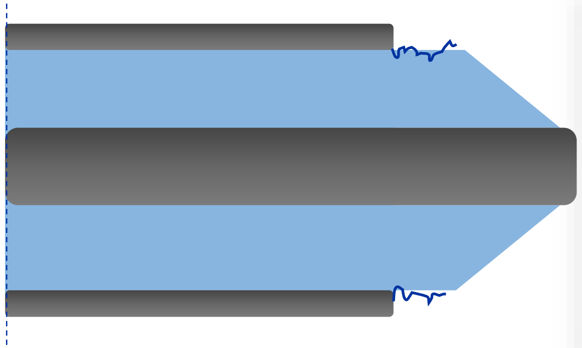
INTERNAL PD





Voids in glass – fiber composite

SURFACE PD



Effect of PD in motor slots

The erosion of the cavity forms a pit that grows deeper causing the complete breakdown of the insulation. This process is called **electrical treeing** and it can develop quickly (e.g. <1h).

- PD is the breakdown of a portion of fluid in an insulation system, which does not bridge the space between the electrodes.
- PD in solids occurs in gas-filled cavities (Paschen Law applies)
- PD contributes to the "electrical ageing" (particularly under AC voltage).

Dielectrics

Properties and Breakdown Mechanisms

Gas

+

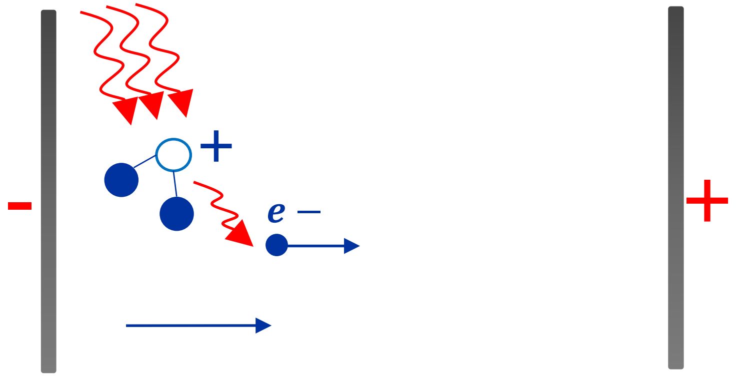
- ☐ Self-healing
- ☐ Permittivity ≈ 1
- ☐ Inexpensive

–

- ☐ Low dielectric strength
- ☐ Leaks

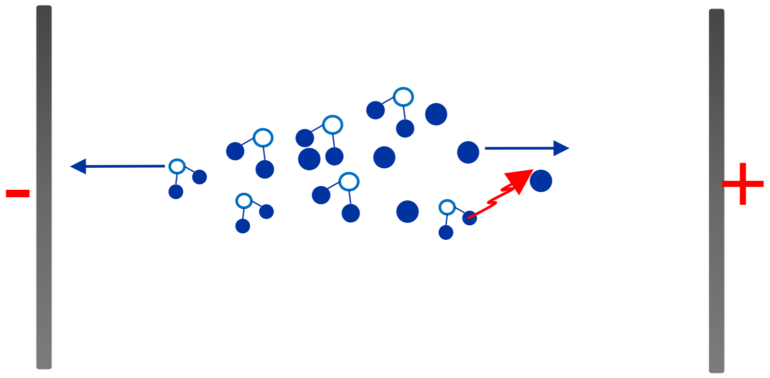
Gas – Townsend breakdown mechanism

IONIZATION



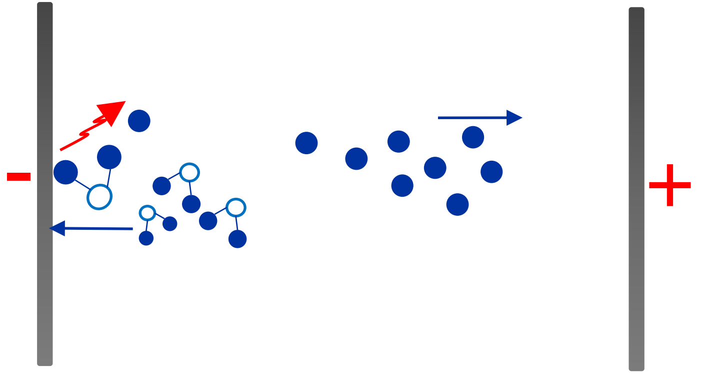
- All we need is a **free electron** released by **ionization of a gas molecule** (by light, cosmic radiation, radioactive radiations, etc.).
- The electron is **accelerated (F = qE)** in the direction of the electric field till it **collides with a gas molecules**.
- The average distance travelled prior a collision is the **mean free path λ** (<1 mm at 1 bar)

AVALANCHE



- **Collisions** may lead to **ionization, excitation, attachment**.
- Each ionization liberates electrons that, in turn, will lead to more collisions, ionizations and so forth.
- An **electron avalanche** is created.

BREAKDOWN

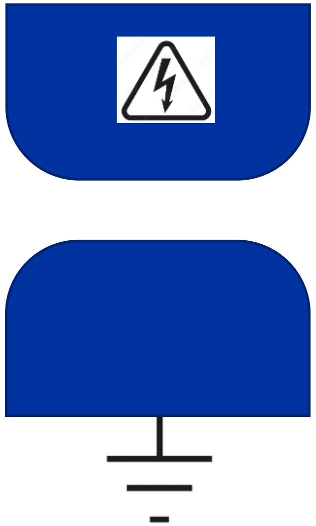


- The avalanche is not sufficient to create the breakdown conditions.
- **Secondary electrons** must be released by the cathode:
  - Ion impact
  - Photon impact
  - Field emission (high vacuum)
  - …

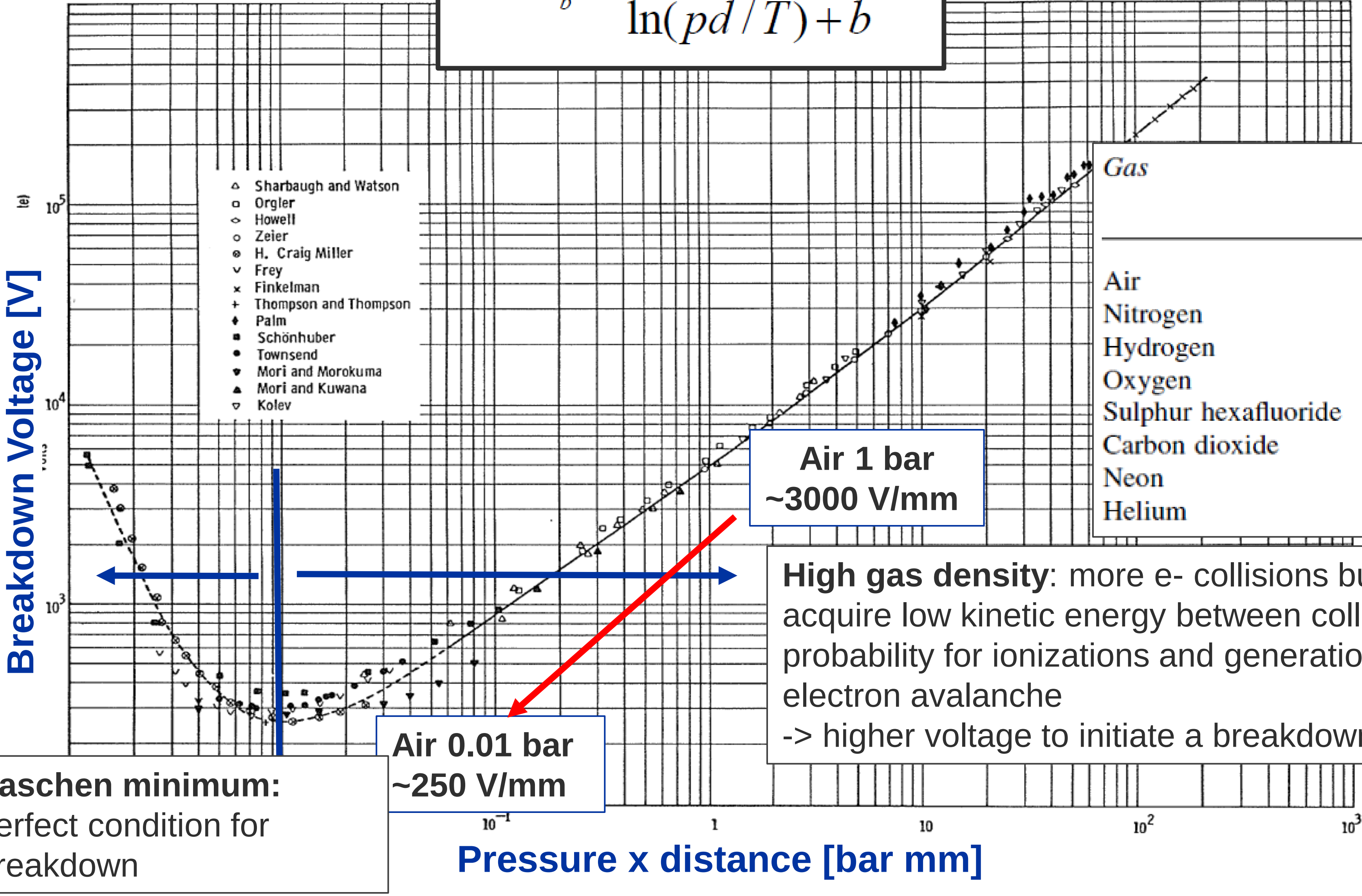
The mechanism is also influenced ion transport phenomena (mobility, diffusion) and the electron attachment (negative ions)

Paschen Law

$$V_b = \frac{a(pd/T)}{\ln(pd/T)+b}$$



Low gas density: Low rate of e- collisions; therefore, less probability of ionizations and generation of an electron avalanche -> higher voltage to initiate a breakdown



Air 1 bar
~3000 V/mm

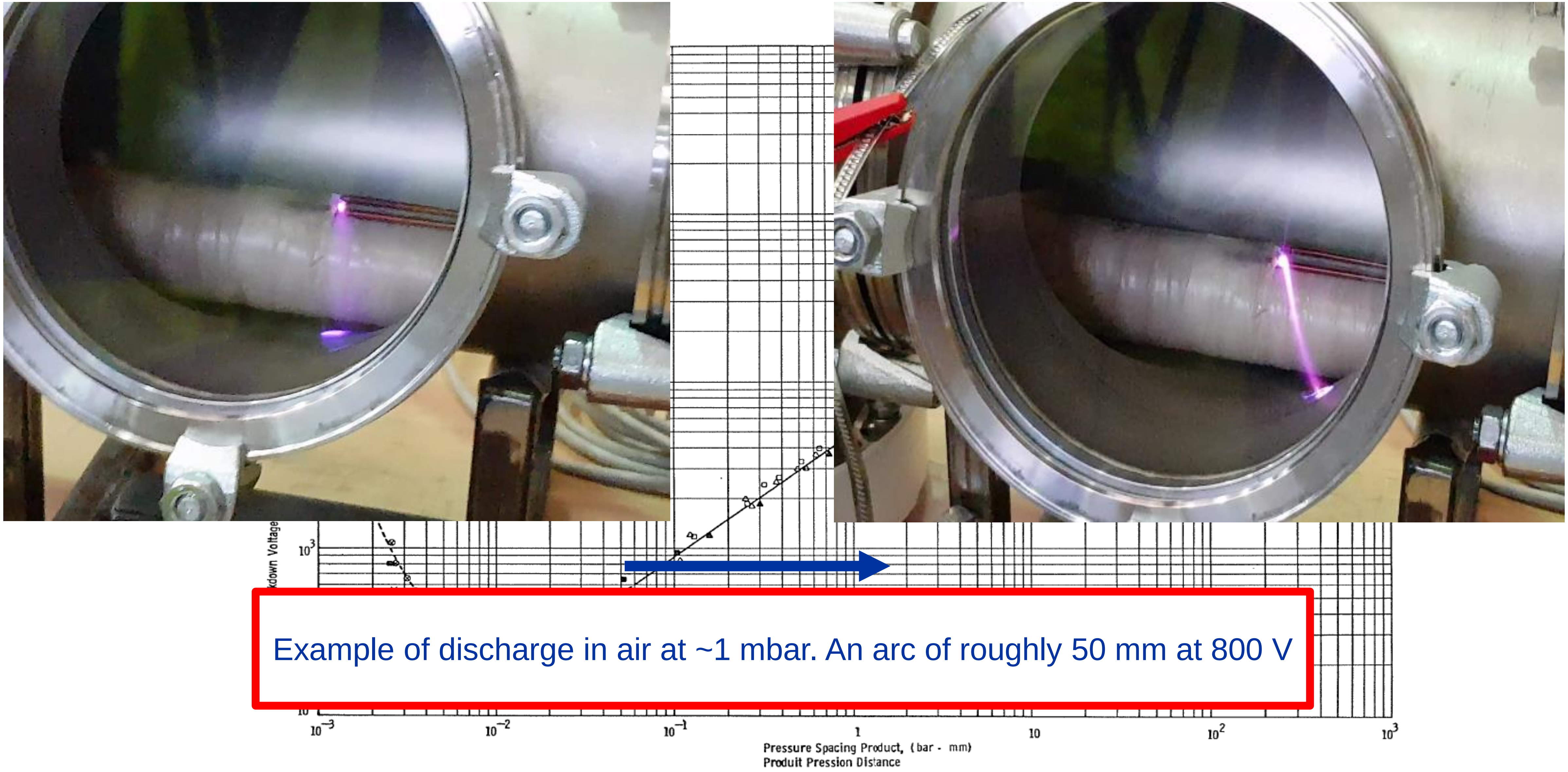
Air 0.01 bar
~250 V/mm

Paschen minimum: perfect condition for breakdown

High gas density: more e- collisions but electrons acquire low kinetic energy between collisions; lower probability for ionizations and generation of an electron avalanche
-> higher voltage to initiate a breakdown

Gas	$(pd)_{\min}$ *torr cm*	$V_{b\min}$ *volts*
Air	0.55	352
Nitrogen	0.65	240
Hydrogen	1.05	230
Oxygen	0.7	450
Sulphur hexafluoride	0.26	507
Carbon dioxide	0.57	420
Neon	4.0	245
Helium	4.0	155

Paschen Law



Example of discharge in air at ~1 mbar. An arc of roughly 50 mm at 800 V

Paschen discharge

“Paschen tight” insulation are particularly important for magnets operating in insulating vacuum:

- Nuclear Fusion machines
- Conduction cooled magnets

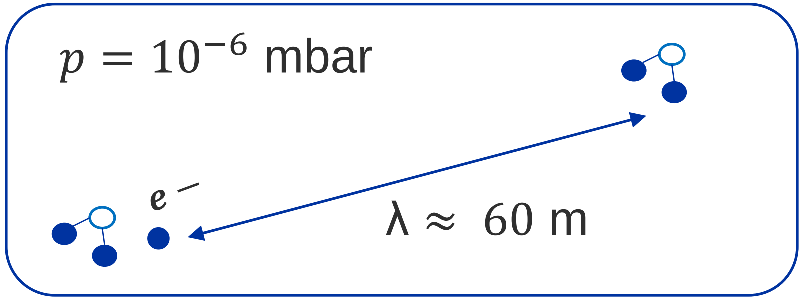
Avoid electrically active parts exposed to vacuum (a gas leak can always occur…)

~ 1 MJ melts 1 kg
of stainless steel !

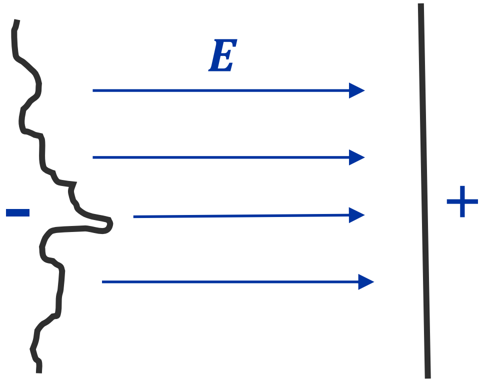
Vacuum

Characteristics

- ❑ High dielectric strength (~ 30 – 40 kV/mm)
- ❑ Self-healing
- ❑ No dielectric losses
- ❑ Non-flammable



Breakdown mechanism



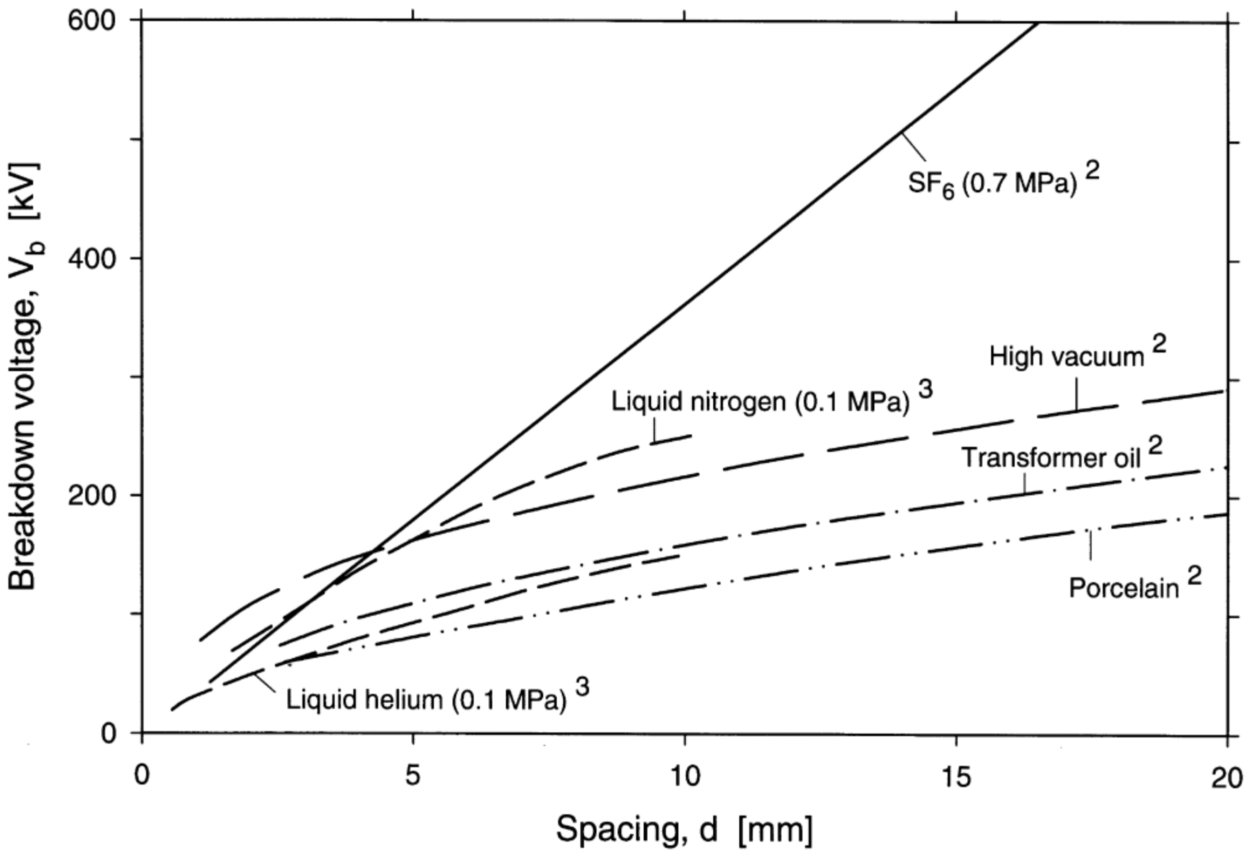
Protrusions are source of electrons at very high fields (~MV/mm).
Field-induced emission grows with the temperature

➡

Local resistive heating creates local metal evaporation.
Desorption of gases (trapped in the metal) and particles causes the breakdown

Liquids

- ❑ Dielectric strength higher than gases
- ❑ Low permittivity. He and N_2 are non-polar
- ❑ Efficient coolant



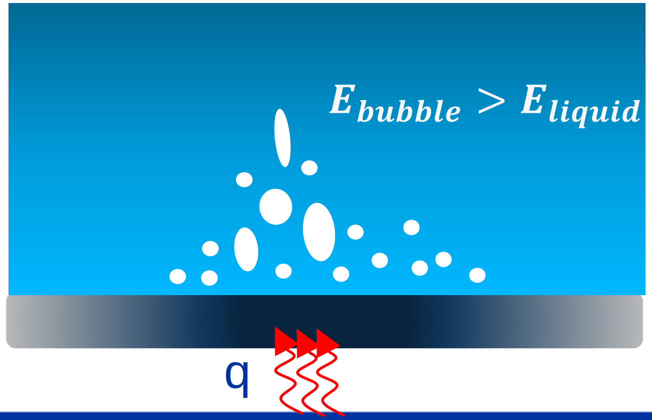
J. Gerhold - Properties of cryogenic insulants; Cryogenics 38 (1998) 1063–1081

Breakdown Mechanism in Liquids

Breakdown in liquids is complex phenomenon as it is influenced by the presence of **particles** and **bubbles** moving in the liquid by buoyancy or electric fields (dielectricphoresis).

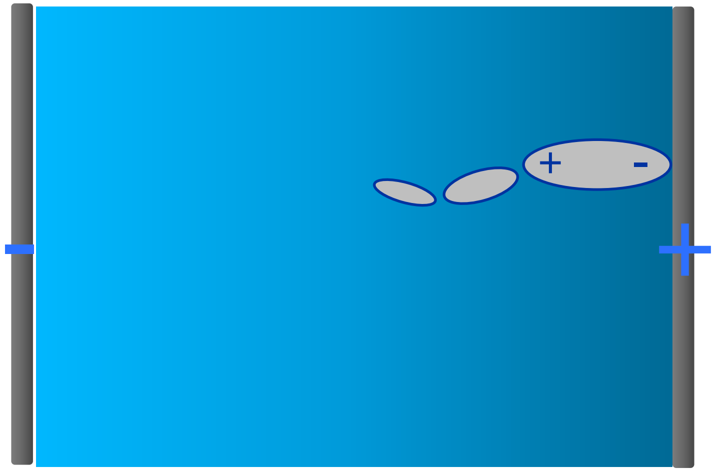
Bubbles

- Hot spots or quench of superconductors causes **evaporation of cryogenic fluids**.
- **Enhanced E-field in the bubbles** where **breakdown initiates**



Particles

- **Dust particles, frozen foreign gases, metal chips** cause a serious problem since they are **pushed towards high field regions**.
- Higher the particle permittivity larger is the force and the electric field distortion around it.



Solid Dielectrics

\+

☐The dielectric acts as **mechanical support**

☐ High breakdown strength

−

☐ Breakdown is destructive

☐ Complex manufacturing processes

☐ Compatibility with the operating environment (vacuum, radiation, etc.)

☐ Higher permittivity and dielectric losses

Breakdown in solids

The breakdown in solids is not ascribable to a single phenomenon

$$E_{\text{allowable}} = E_{\text{nominal}} * f_1*f_2*f_3*\ldots*f_n$$

$E_{\text{max calculated}} < E_{\text{allowable}}$

E_{nominal} is the dielectric strength from datasheets or directly measured in your laboratory (e.g. IEC 60243)

f_x = derating factor:

- Volume and thickness (volume effect)
- (elevated) Temperature
- Electrodes geometry
- Voltage type (AC, DC, impulse)
- Electrical ageing
- Mechanical stress
- Thermo-mechanical stress
- Radiation
- Etc…

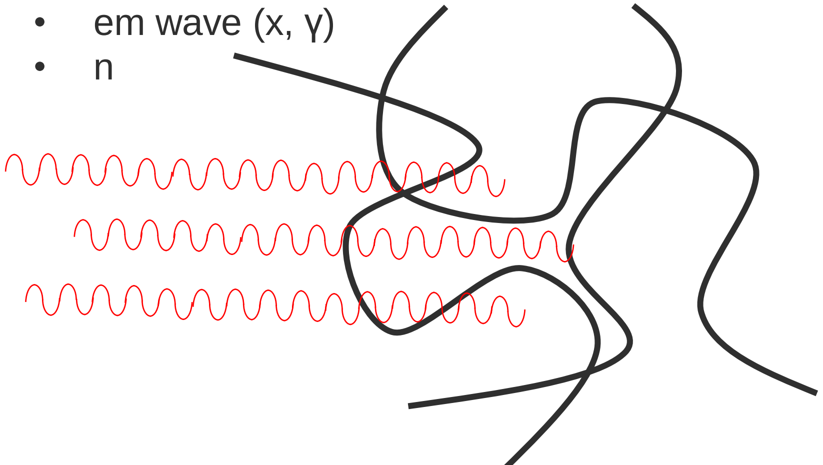
- Pure “dielectric” considerations are not sufficient to design a robust insulation system.
- Extensive testing (HV, mechanical and thermomechanical fatigue, etc.) is necessary to validate the design choices. Starting with material characterization, mock-ups, short coil, etc.

Example Cryogenics, Volume 83, April 2017, Pages 64-70 AND Cryogenics, Volume 98, March 2019, Pages 113-124

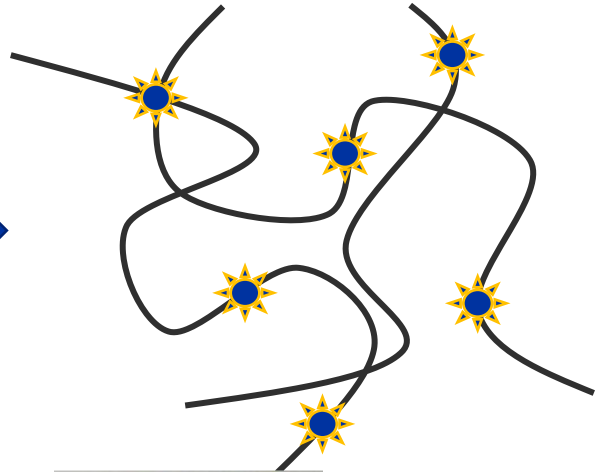
Effect of radiations

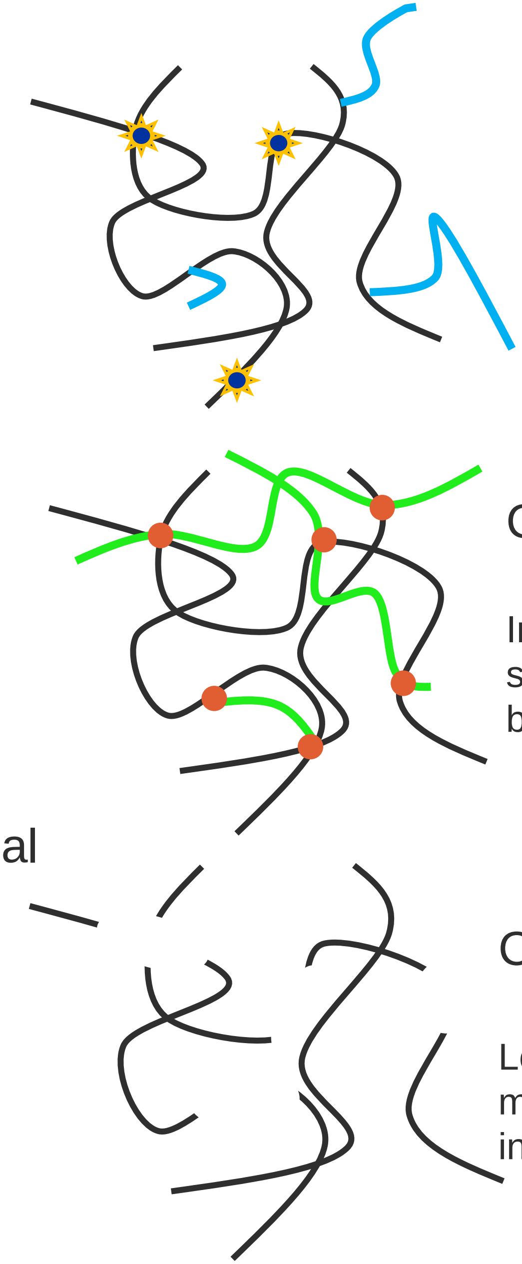
Radiation

- Particle (p+, α, β)
- em wave (x, γ)
- n



Free radicals





Grafting

Cross-linking

Increase of stiffness but also brittleness

Chain-scission

Loss of mechanical integrity

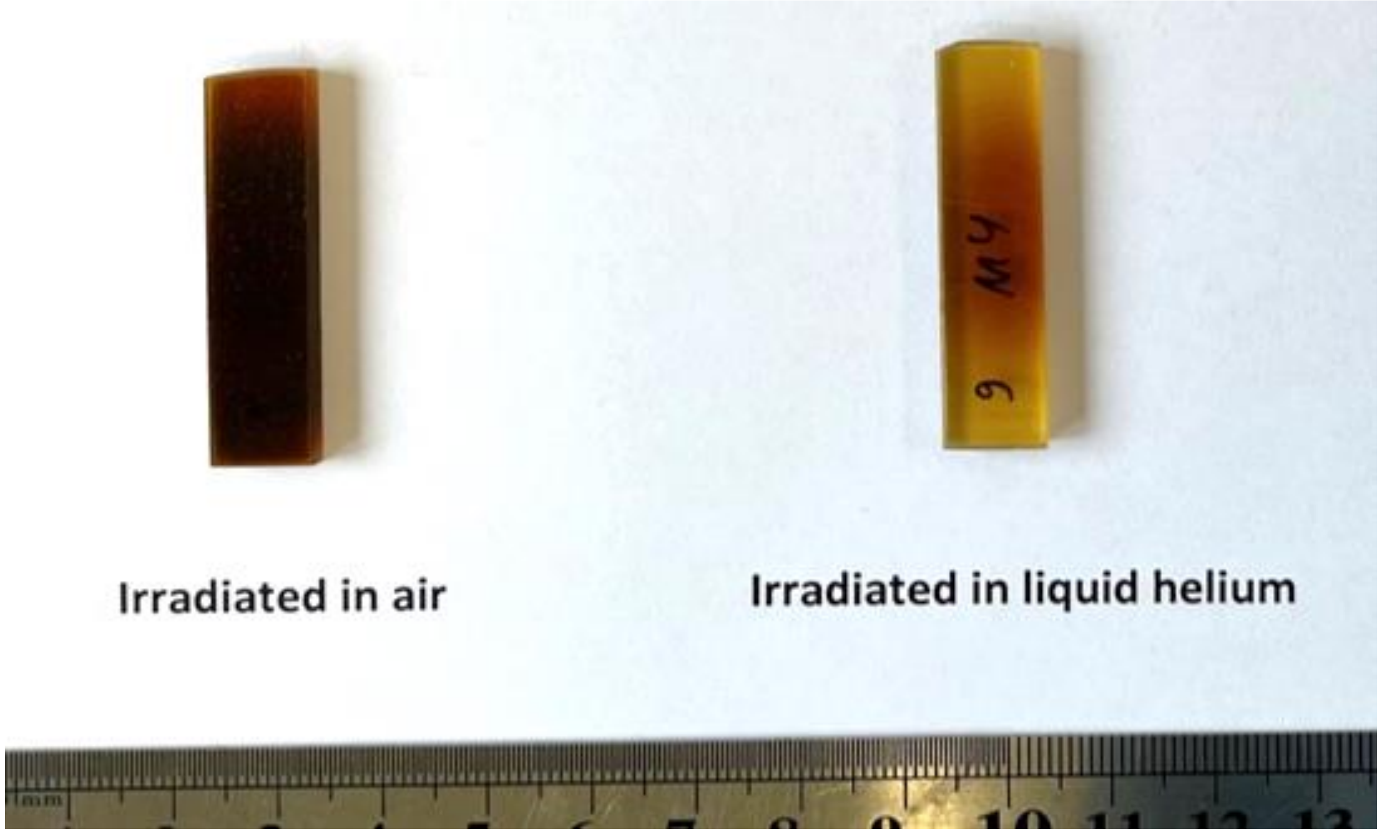
IEC 60544 Electrical insulating materials – Determination of the effects of ionizing radiation

Some other physical effects:

- oxidation
- discoloration
- gas evolution / swelling

Radiation environment

The **irradiation environment** can have a strong effect on aging rate of epoxies. In particular, the absence of oxygen may lead to a milder degradation of the polymer structure.



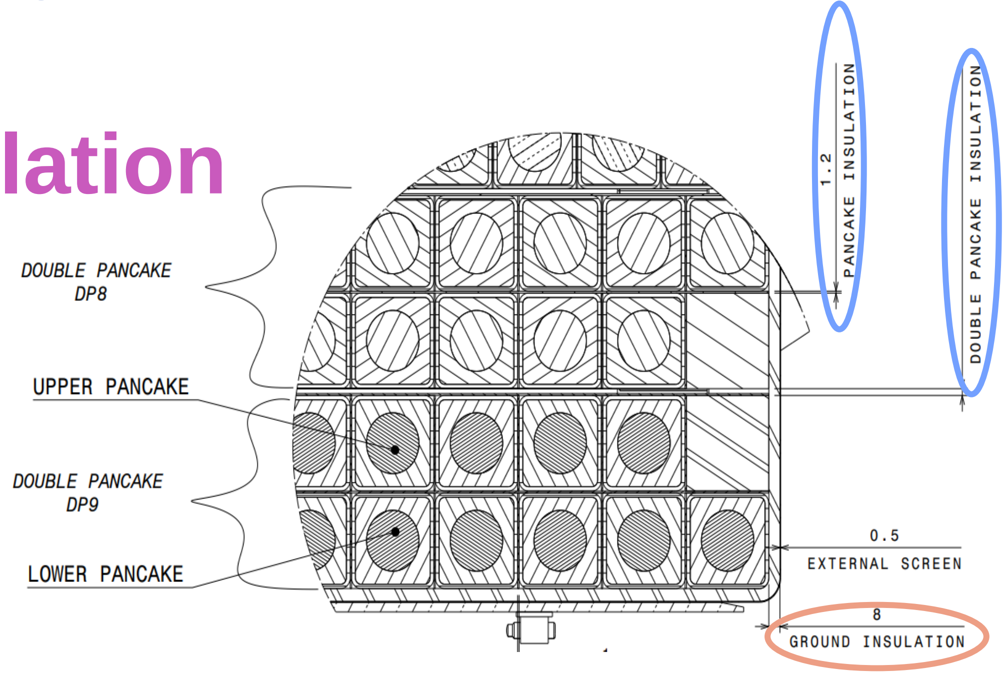
He cryostat for proton irradiation at IRRAD facility with support of the Cryolab (CERN),

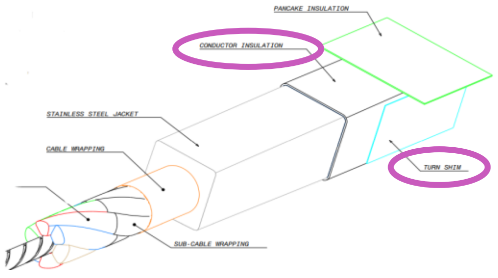
Courtesy of C. Scheurelein, D. Parragh

Insulation systems for magnets

Magnet Insulation System

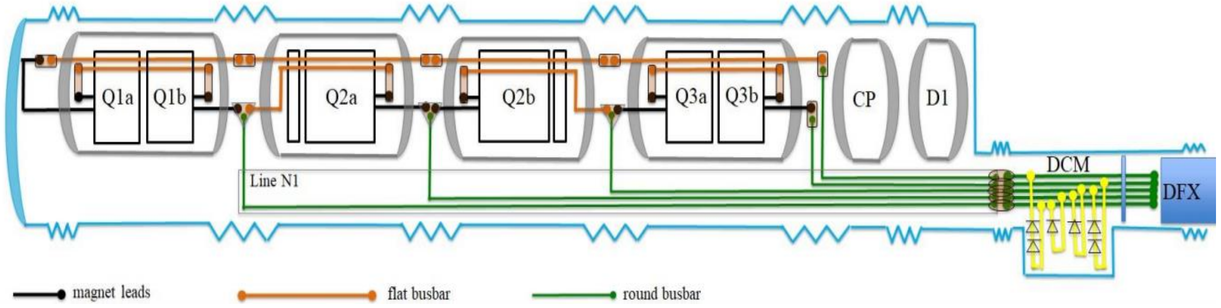
- **Turn/Conductor insulation**
- **Layer insulation**
- **Ground insulation**





We should not forget the magnet is part of a **system** which includes wiring, instrumentation, splices, spacers and various insulators.

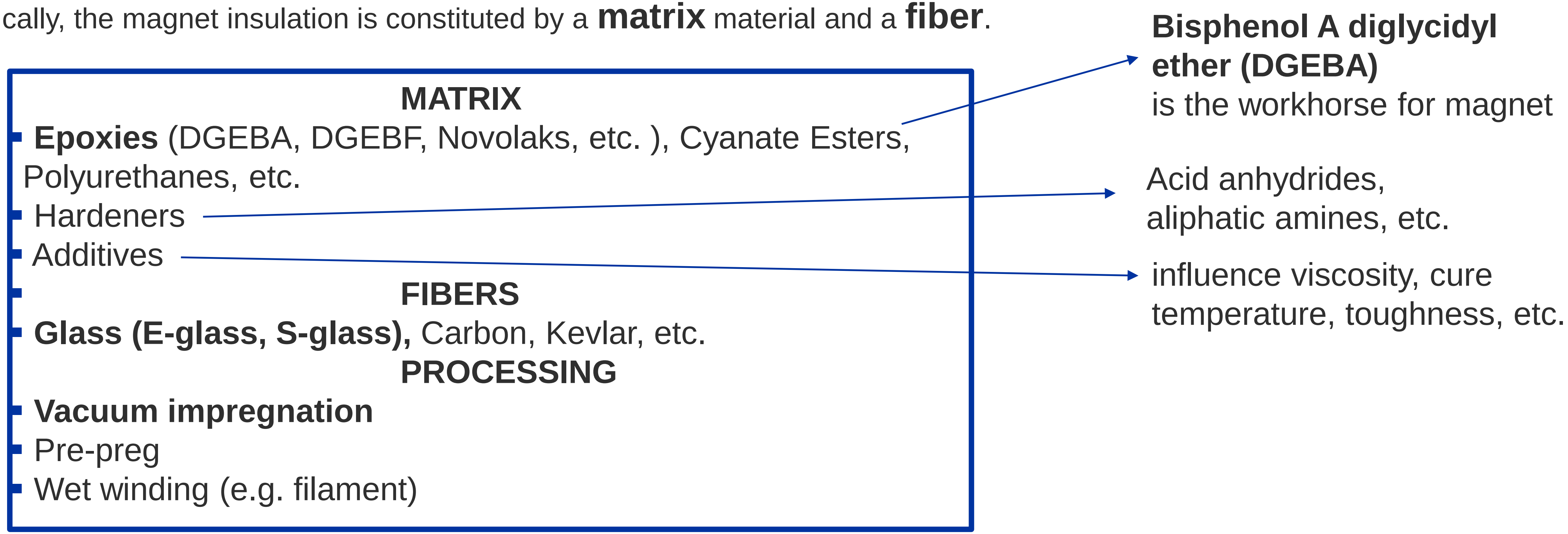
Designing the insulation with a system perspective, this is **INSULATION COORDINATION**



Example of interconnected magnet system

Composites

- **Composites** main advantage is their **mechanical robustness**.
- **Magnets during operation are subjected to elevated mechanical and thermo-mechanical loads** with all sort of profile (shear, compression, compression-shear, tensile) which are cause of possible failure mechanisms.
- Typically, the magnet insulation is constituted by a **matrix** material and a **fiber**.



MATRIX

- **Epoxies** (DGEBA, DGEBF, Novolaks, etc.), Cyanate Esters, Polyurethanes, etc.
- Hardeners
- Additives

FIBERS

- **Glass (E-glass, S-glass),** Carbon, Kevlar, etc.

PROCESSING

- **Vacuum impregnation**
- Pre-preg
- Wet winding (e.g. filament)

Bisphenol A diglycidyl ether (DGEBA) is the workhorse for magnet

Acid anhydrides, aliphatic amines, etc.

influence viscosity, cure temperature, toughness, etc.

Bonding between matrix and fiber is fundamental to express full composite potential. **Fiber/matrix debonding results in failure of the composite**. Other causes are matrix cracking and fiber breaking.

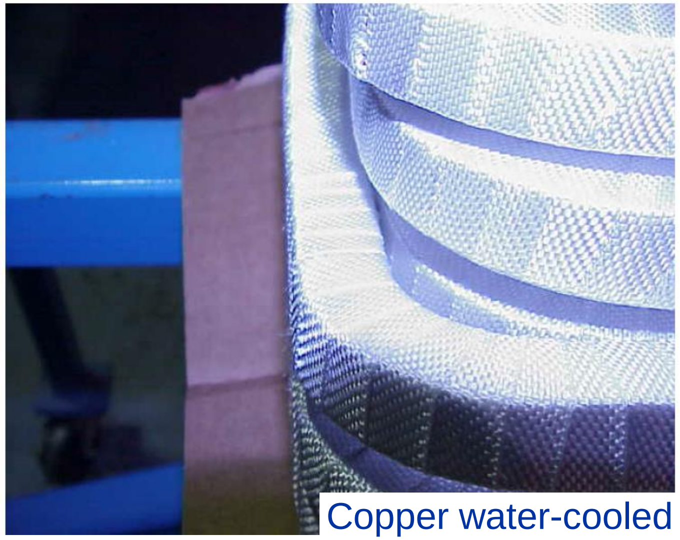
Magnet (composite) insulation manufacturing

Resistive magnets

- Wound half-lapped E or S glass insulation.

Typically:

- **Conductor insulation thickness 0.5 mm**
- Ground insulation thickness 1.5 mm



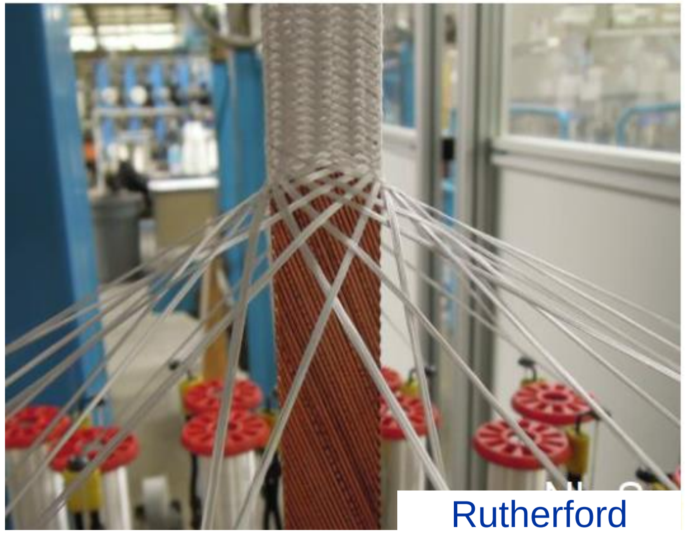
Copper water-cooled

Superconducting magnets for HL-LHC*

- Braided insulation S2-glass (to minimize thickness).

Typically:

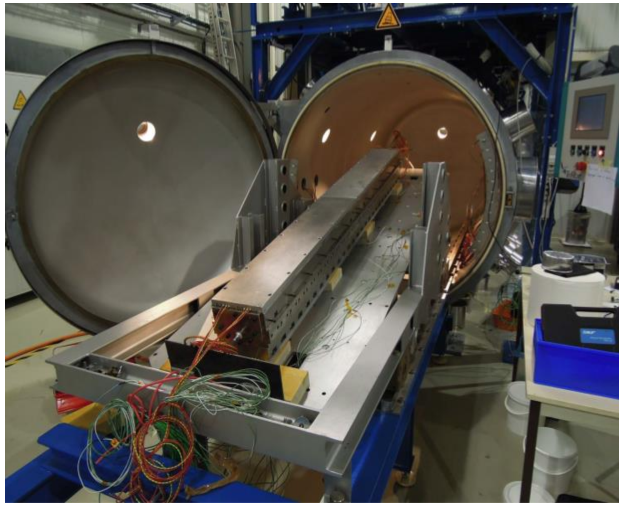
- **Conductor insulation thickness 0.150 mm**
- Ground insulation (Kapton sheet) 0.125 mm



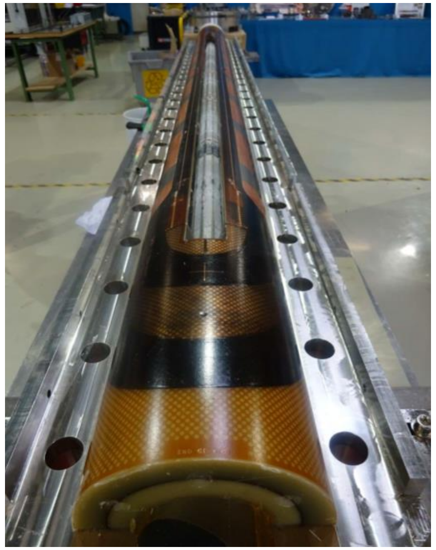
Rutherford

Vacuum impregnation

- **Degassing** at < 1mbar resin + Hardener (to remove air and humidity), same for the mold
- **Impregnation** (control time and speed)
- **Curing cycle** (T impregnation -> Tgel -> T polymerization)



Final product



*first project introducing Nb3Sn impregnated coil in an accelerator

Dielectric barriers

Electrical barriers can be introduced in the fiber-glass insulation to **increase the dielectric strength** of the insulation system.

Some reasons for introducing **dielectric barriers**:

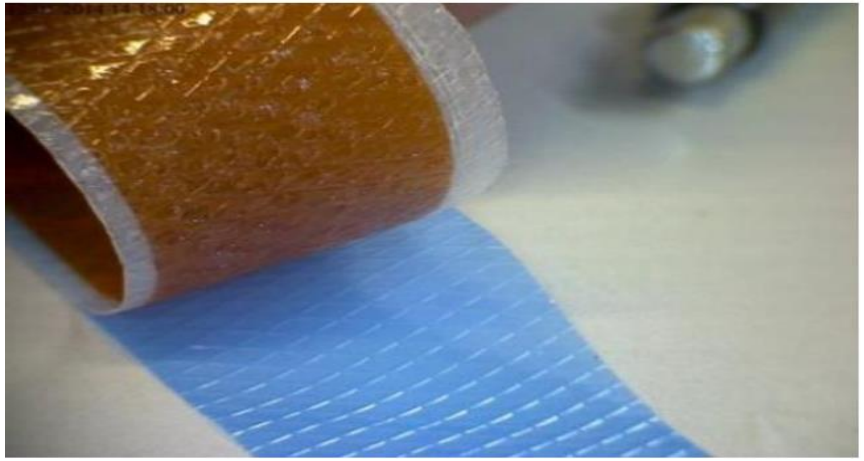
- Epoxy resin are prone to crack at cryogenic temperature
- The high temperatures and radiation doses impose a reinforcement
- The voltage is high (> 5 kV)

Mica or Kapton **dielectric barrier**
Fiberglass + resin is the **mechanical reinforcement**

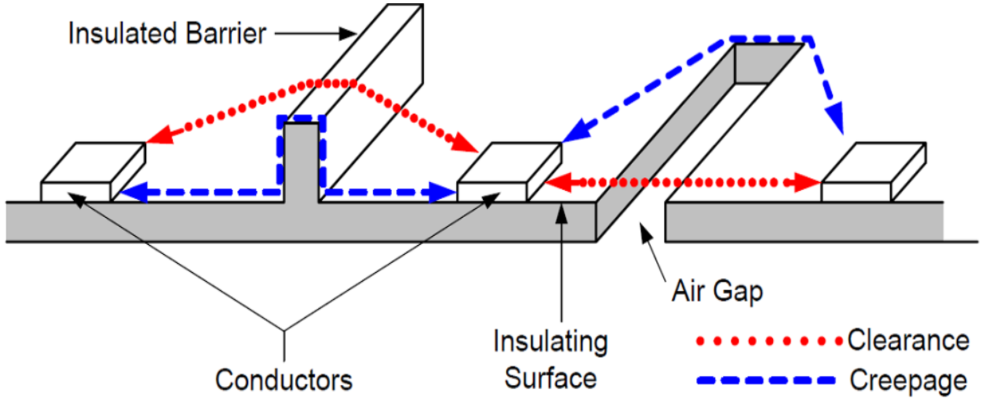
The increase of dielectric strength comes at the cost of the mechanical strength, in particular the shear strength

Mica - Glass

Kapton - Glass



Creepage and clearance distances



CLEARANCE = minimum distance through air spacing

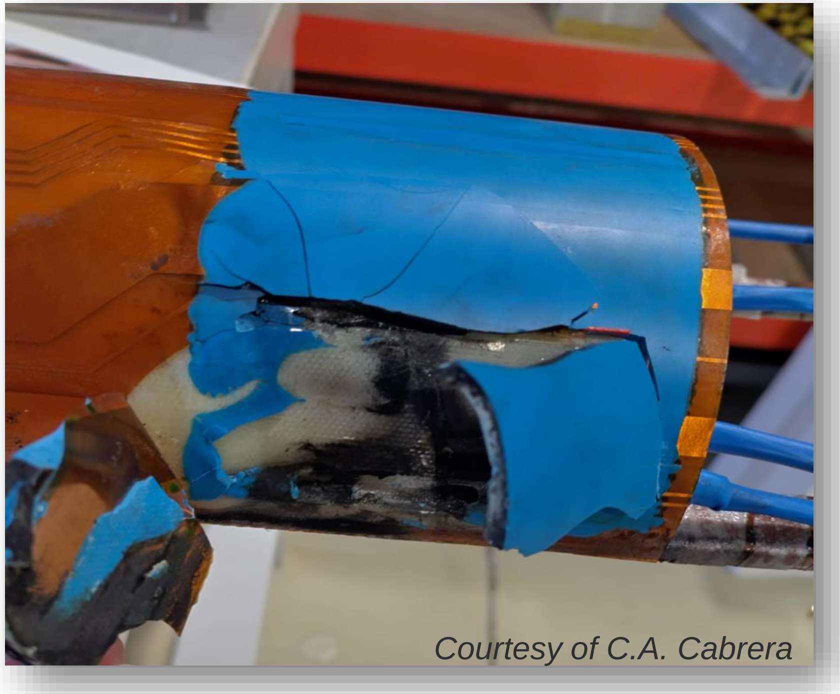
CREEPAGE = minimum distance over surface spacing

- Creepage distances may arise between instrumentation wires, leads terminations, splices, etc. A creepage distance may also appear after an insulation failure (e.g. debonding of resin or delamination of insulation layers)
- There are standards for electronic and electrical equipment (e.g. UL840), but none for magnets.

Applying the UL840 on printed circuit boards for peak voltage of ~1000 V the creepage distance is 1.3 mm. We should be much more conservative for magnets (large energy stored).
Example: for the same peak voltage (1000 V) applying a S factor = 5 and considering the environment/gas.

Air (flashover ~3000 V/mm) → d = 1.3mm x 5 = **6.5 mm**

He (flashover ~300 V/mm) → d = 1.3mm x 5 x 10 = **65 mm**



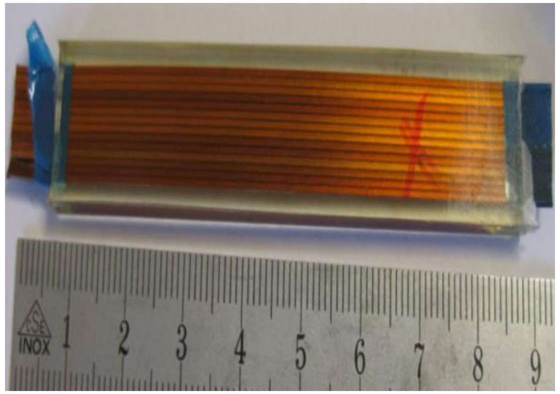
Courtesy of C.A. Cabrera

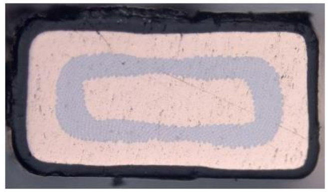
Magnet wires insulation

Enameled wires (coatings)

Poly Amide-Imide (PAI) used in resistive magnets

Polyvinyl alcohol (PVA) used in some Nb-Ti



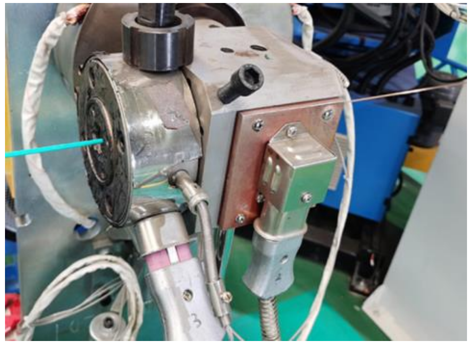


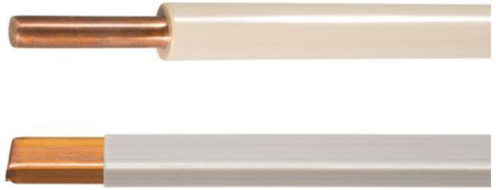
Nb-Ti PVA insulated. Ribbon cable made of 15 Nb-Ti wires and impregnated with epoxy (MCBY corrector)

Extruded wires (thermoplastics)

Polyether ether ketone (PEEK)

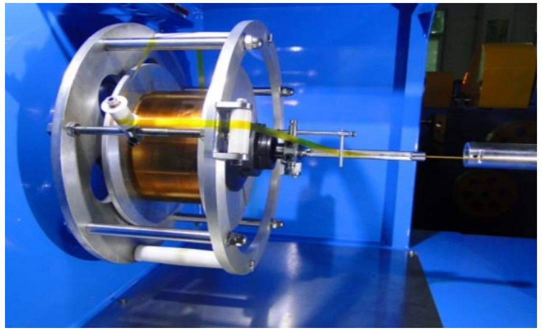
Polyimide (PI)





Taped insulation:

Polyimide (PI) or Kapton (trademark)



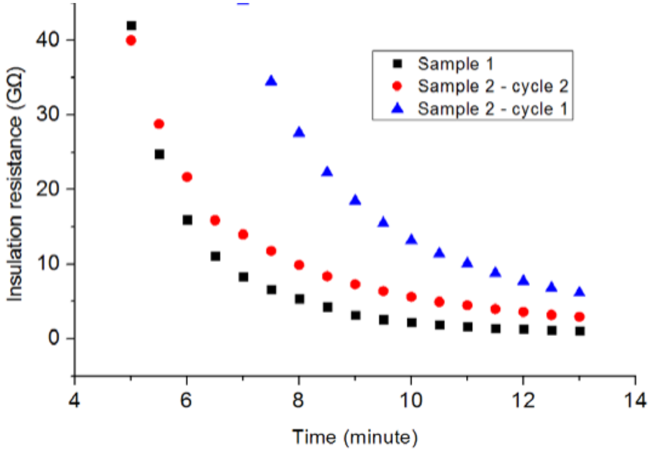
Inorganic insulation – Mineral insulated cables (MIC)

+

- ☐ High temperature resistance (> 300 °C)
- ☐ High radiation resistance (> 100 MGy)

−

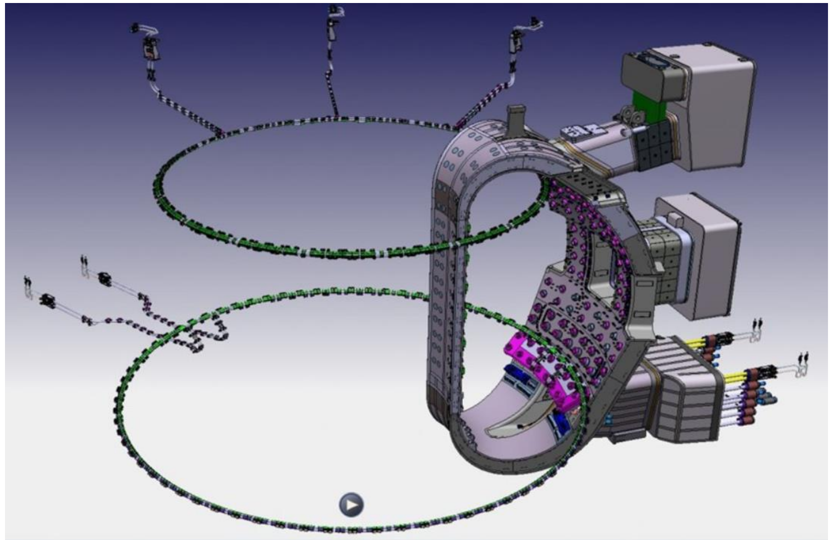
- ☐ Limited voltage withstand (~ few kV/mm)
- ☐ Hygroscopic (insulation resistance drop quickly upon exposure to air)

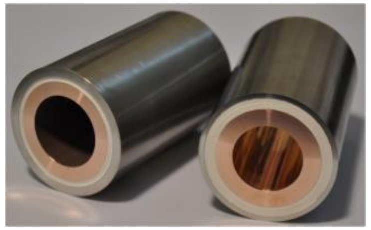


Conductor size, outside nominal square	0.57"	14.5 mm
inside nominal square	0.26"	6.6 mm
Conductor wall thickness, min.	0.09"	2.3 mm
Insulation thickness, nominal	0.05"	1.3 mm
minimum	0.03"	0.8 mm
Sheath thickness :	0.035 ± 0.005"	0.9 ± 0.1 mm
Conductor material	copper 100% I.A.C.S. soft annealed	
Sheath material	commercial copper, soft annealed	
Insulation material	compacted magnesium oxide	
Minimum bending radius	2.5"	63.5 mm
Required factory length (sheath length)	230 $^{+1.6}_{-0.0}$ ft.	70 $^{+0.5}_{-0.0}$ m
Weight	1.4 lbs/ft.	2.1 kg/m

Hydraulic :

MSSB splitter magnet (CERN)
MgO MIC water-cooled cable





In-vessel coils (ITER)
MgO MIC water-cooled

High Voltage Testing

Voltages in magnets

We distinguish voltages at **normal operating conditions (NOC)** and **fault conditions (FC)** which often includes a double fault scenario.

Voltages for superconducting magnets

- NOC During a quench, resistive voltage develops across the winding
- NOC During the energy discharge through an external dump resistor
- Combined fault scenarios:
  - FC Dump discharge + Ground fault
  - Multiple failures of protections (like quench heaters)
  - Etc.

Voltage in resistive magnets

- Voltage is developed by the power supply to feed the current through the coil (L and R) -> $V = L\,di/dt + Ri$ NOC
- Rise time!
- Overvoltage during ground fault FC
  - Ground fault

High Voltage testing on the magnet lifecycle

During **design & manufacturing**

Type test
(Sample / Prototype)

Routine test
(Quality control)

Factory acceptance test
(Final product)

During **system assembly & commissioning**

Site-acceptance test
(Final product)

Installation/Assembly test and check
(sub-system)

During **operation**

Performance check
(system or sub-system)

Maintenance and troubleshooting
(system or sub-system)

When doing HV test?

On each phase of the magnet lifecycle

Why HV test ?

One of the main (if not the only) test to assess the **dielectric and mechanical integrity** of the coil

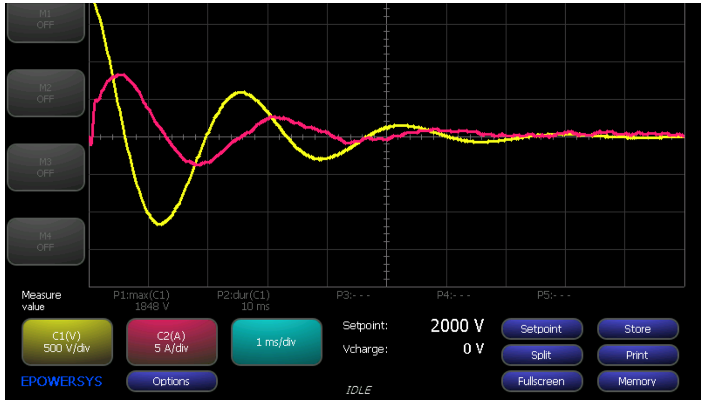
📈 Complexity

📉 Test voltage
(not lower than NOC voltage)

High Voltage test techniques

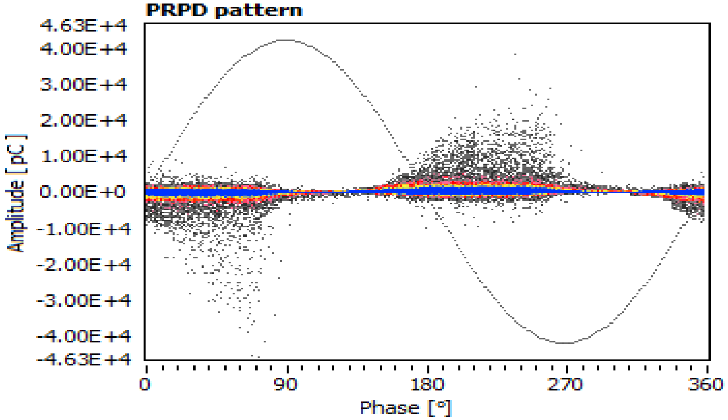
Go/no go test is a procedure used to verify the **electrical insulation integrity.** The primary function is proof the system/device can **withstand the test voltage** without breakdown or excessive leakage current. Performed at voltage higher than normal operating voltage.

- **Hipotest** (ground insulation)
- **Impulse test** (turn-to-turn insulation and ground insulation)
- **Paschen test**


Measure value
P1:max(C1) 1848 V
P2:dur(C1) 10 ms
P3:- - -
P4:- - -
P5:- - -
C1(V) 500 V/div
C2(A) 5 A/div
1 ms/div
Setpoint: 2000 V
Vcharge: 0 V

Diagnostic tests are specialized procedures to **assess and locate an electrical fault** or determine the **health condition** of the of the insulation to identify maintenance actions. Typically performed at normal operating voltage or slightly above.

- **Insulation resistance**
- **Partial Discharge**
- **Tan delta** (dielectric losses)



References & Acknowledgments

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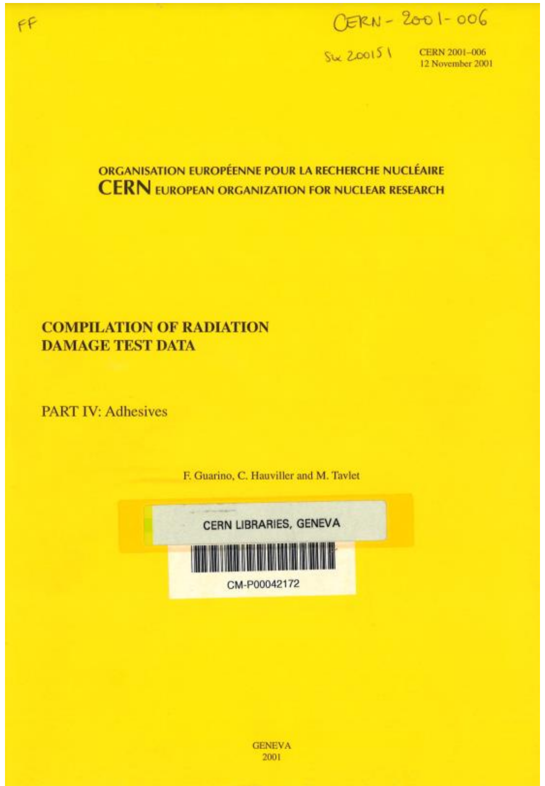
- **F. H. Kreuger – Industrial High Voltage - Volume I, II, II, Delft University**
- E. Kuffel, et al. – High Voltage Engineering: Fundamentals
- P. Morshuis - Interfaces: to be avoided or to be treasured? - 2013 IEEE International Conference on Solid Dielectrics
- D. Evans - Resins for Superconducting Magnet Construction – An Overview of Requirements, Processing and Properties 2020
- Radiation damage compilation – CERN yellow book



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CERN 2001–006
12 November 2001

ORGANISATION EUROPÉENNE POUR LA RECHERCHE NUCLÉAIRE
CERN EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

COMPILATION OF RADIATION
DAMAGE TEST DATA

PART IV: Adhesives

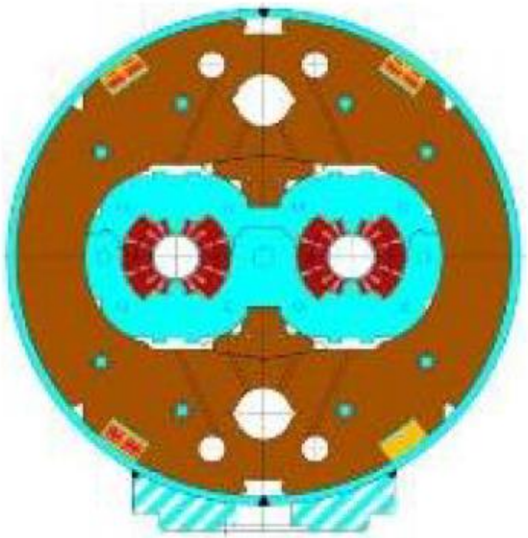
F. Guarino, C. Hauviller and M. Tavlet

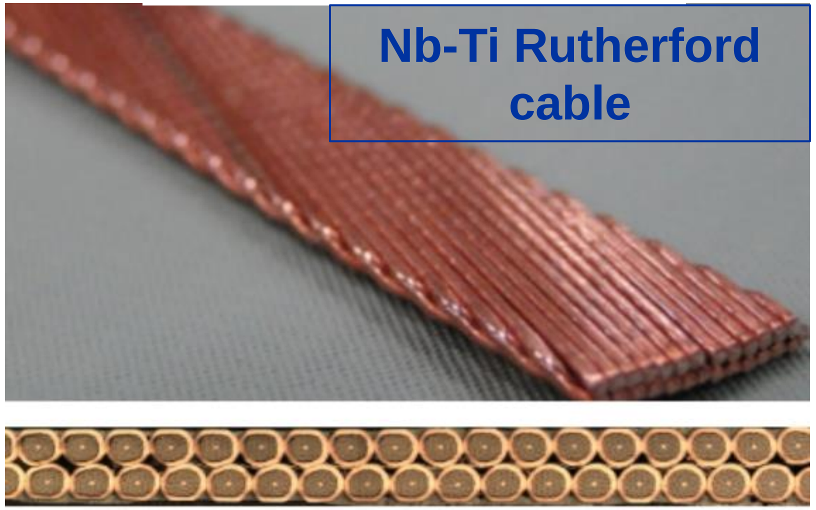
GENEVA
2001

And discussions with colleagues D. Tommasini, A. Milanese, J. Bauche, E. Todesco, M. Bednarek, C. Scheurlein and many others

Extra

LHC Dipole





Nb-Ti Rutherford cable

Conductor Insulation schemes

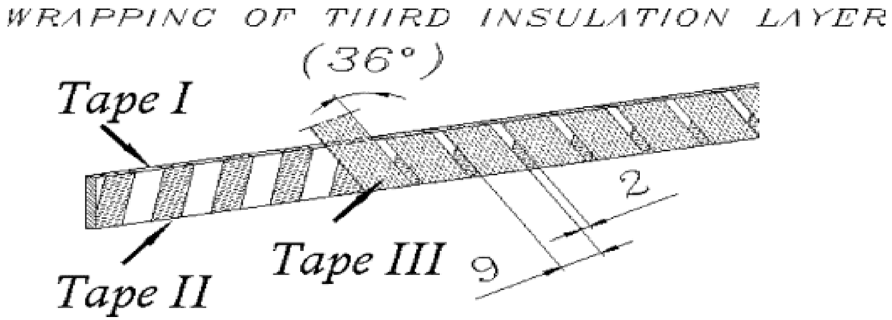


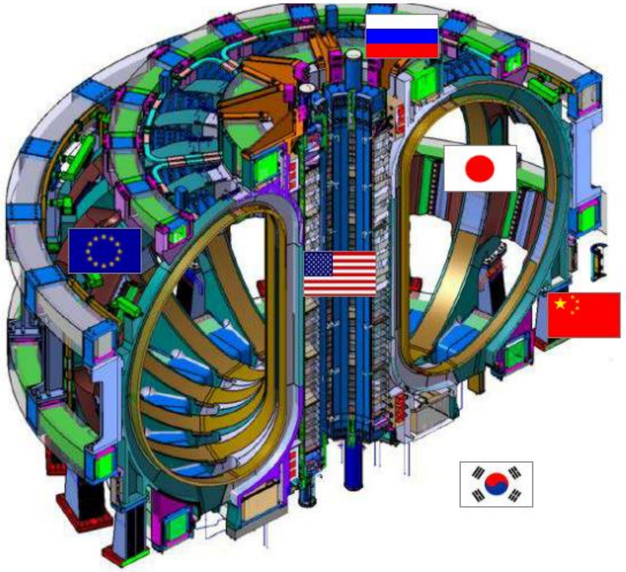
Fig. 2. Layout of cable insulation of the LHC main dipoles and quadrupoles. The detail of the 3rd layer is shown, which consists in a 9 mm wide tape, wrapped spaced by 2 mm to allow helium to penetrate in the coil, adhesive on its outer side to bond adjacent coil turns together.

The cables of the LHC superconducting magnets are insulated by three layers of polyimide films which are supplied in the form of tapes

“LHC Design Report” vol. I, p. 170, (CERN).

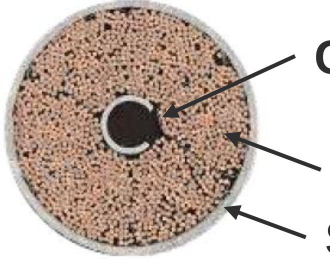
Fusion magnets

ITER Magnet System



Large stored energies 51 GJ
High voltages 30 kV

Cable-in-conduit conductor



Cooling spiral for LHe

SC strands

Stainless steel conduit

Ground Insulation scheme

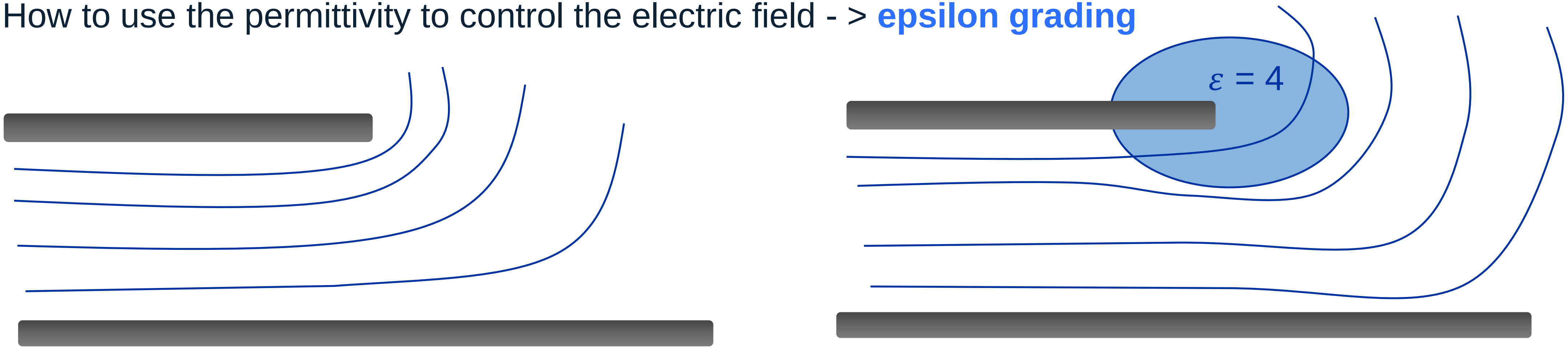
Polyimide acts as **electrical barrier**
Fiberglass + resin is the
mechanical reinforcement

Wrapping the Glass – Kapton tape on conductor and winding pack

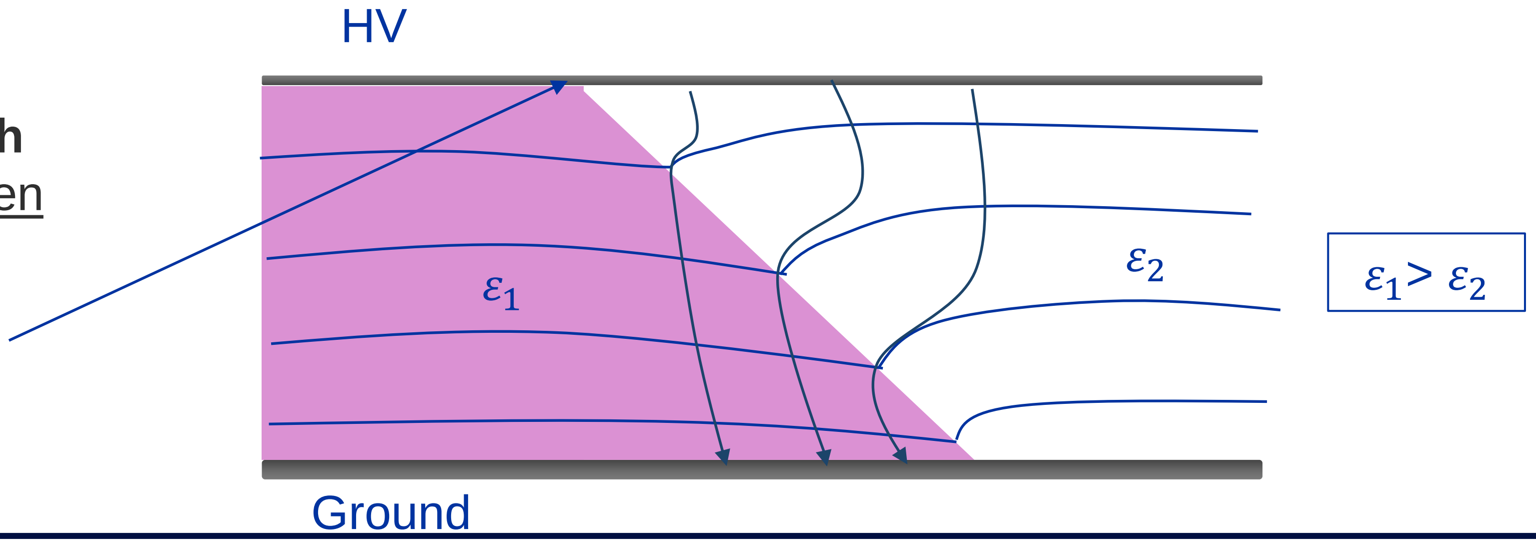
Vacuum Pressure Impregnation (VPI)

Other examples of the “power” of permittivity

How to use the permittivity to control the electric field - > **epsilon grading**

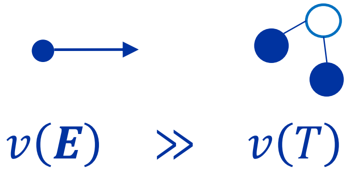


- A **triple junction** is the point of **high field stress** at the boundary between two dielectrics and the electrode
- Dangerous E-field parallel to the interface



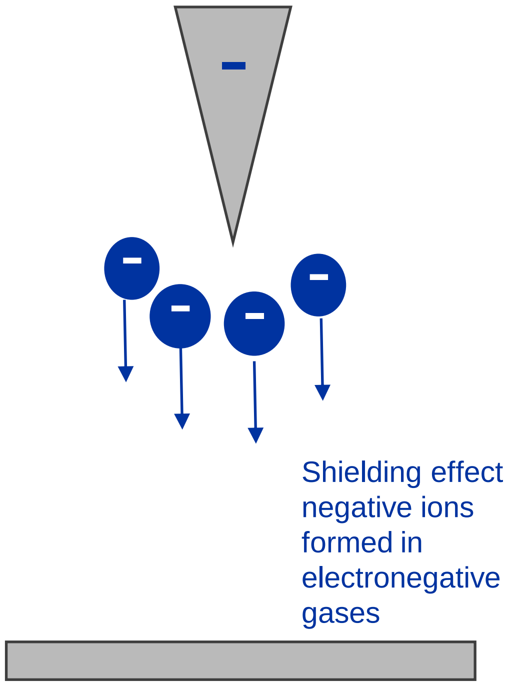
Validity of the Paschen Law

- **Temperature**. The gas breakdown law is valid also at cryogenic temperatures. Dielectric strength of gases at room temperature and cryogenic temperatures is basically the same but the density must be the same to compare the values. The molecule is immobile for the electron.



$$v(\boldsymbol{E}) \gg v(T)$$

- **Electrodes material**. The release of a secondary electron depends on the work function of the metal constituting the electrodes.
- **Uniform electric field**. In case of highly distorted electric field (e.g. needle) pre-discharges (i.e. Corona) creates space charge (e.g. negative ions) that modify the electric field. This is of lesser importance for cryogenic gases like N_2 and He since not electron attaching gases.



Shielding effect of negative ions formed in electronegative gases

- **Gas Purity**. Small quantities of foreign gas species affect the voltage breakdown. Example, higher the helium purity lower the dielectric strength. Small amount of hydrogen (e.g. 3 %) increases considerably the dielectric strength of helium.
- **Gas flow**. The mass flow and direction influence ion’s transport.
- **Low pd values**. At higher pd (e.g. 1 bar – 10 mm or 5 bar – 1 mm) the breakdown is described by the streamer mechanism.

Breakdown in solids

SHORT TERM

- ☐ **Intrinsic breakdown**

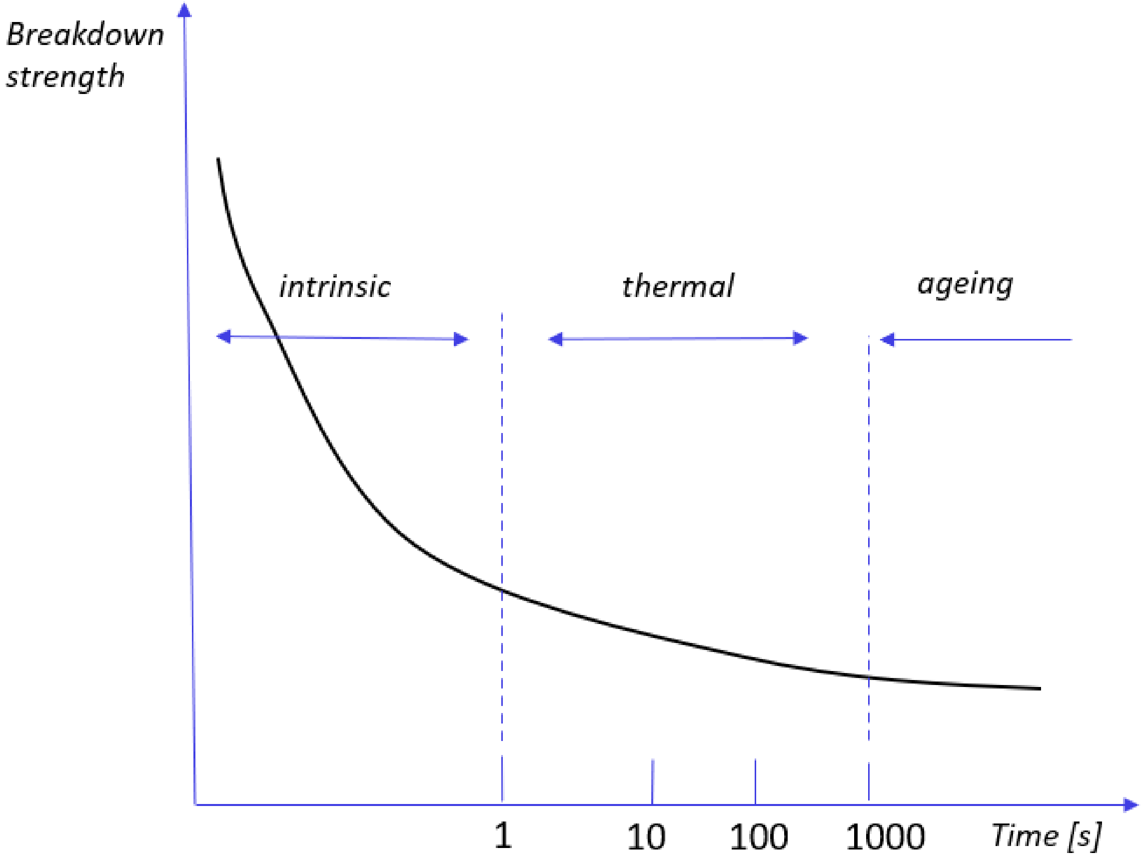
At very high fields a free electron creates a single avalanche that, exceeding a critical size, generates a conductive channel (*streamer*). Moreover, the charge *q* generates at high mechanical pressure in the material.

- ☐ **Thermal breakdown**

The heating rate generated by *dielectric losses* (or *conductive losses* in DC) exceeds the cooling rate generating fast temperature rise and burn out of the insulation.

LONG TERM

- ☐ **Partial Discharge**
- ☐ **Treeing**
- ☐ **Thermo-mechanical induced**
- ☐ **Radiation induced**



Intrinsic Dielectric Strength

❑For liquids dielectrics (as well for solids) the intrinsic dielectric strength may greatly differ from the technical dielectric strength.

❑Intrinsic values are obtained with very short voltage application (< heat), small volumes (< contaminants/defects), filtered and de-ionized liquids, polished electrodes, etc…

LN_2: Intrinsic 170 kV/mm – 200 kV/mm vs. Technical 35 kV/mm – 50 kV/mm

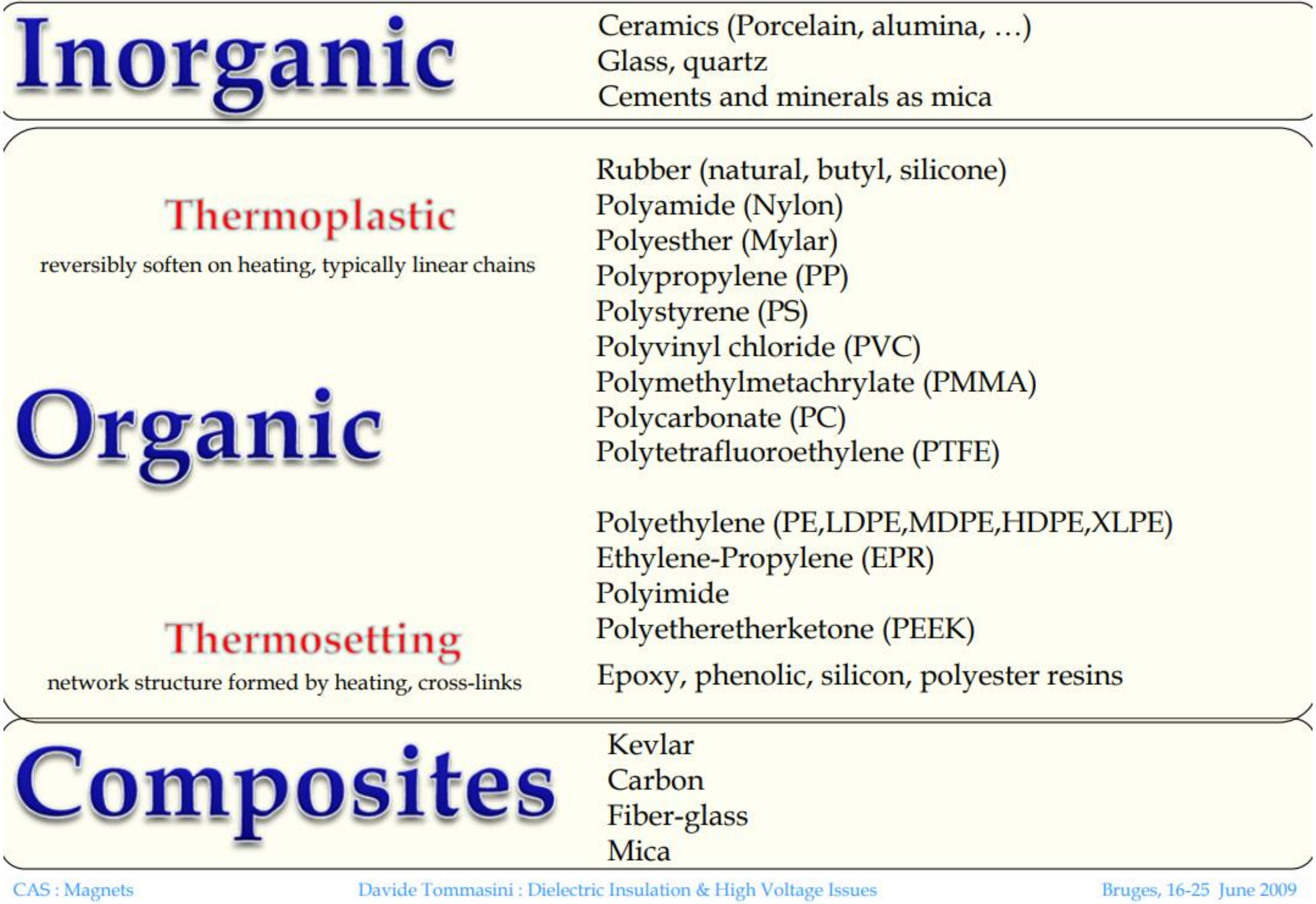
Kapton:

Kapton Datasheet

0.025 mm	0.125 mm	1 mm
300 kV/mm	150 kV/mm	65 kV/mm

Real wire (TPI)

The material datasheet must report the standard test method (e.g. IEC 60243), thickness/volume of the sample, voltage rise time, voltage type (DC, AC, impulse)



Inorganic

- Ceramics (Porcelain, alumina, …)
- Glass, quartz
- Cements and minerals as mica

Organic

Thermoplastic

reversibly soften on heating, typically linear chains

- Rubber (natural, butyl, silicone)
- Polyamide (Nylon)
- Polyesther (Mylar)
- Polypropylene (PP)
- Polystyrene (PS)
- Polyvinyl chloride (PVC)
- Polymethylmetachrylate (PMMA)
- Polycarbonate (PC)
- Polytetrafluoroethylene (PTFE)

Thermosetting

network structure formed by heating, cross-links

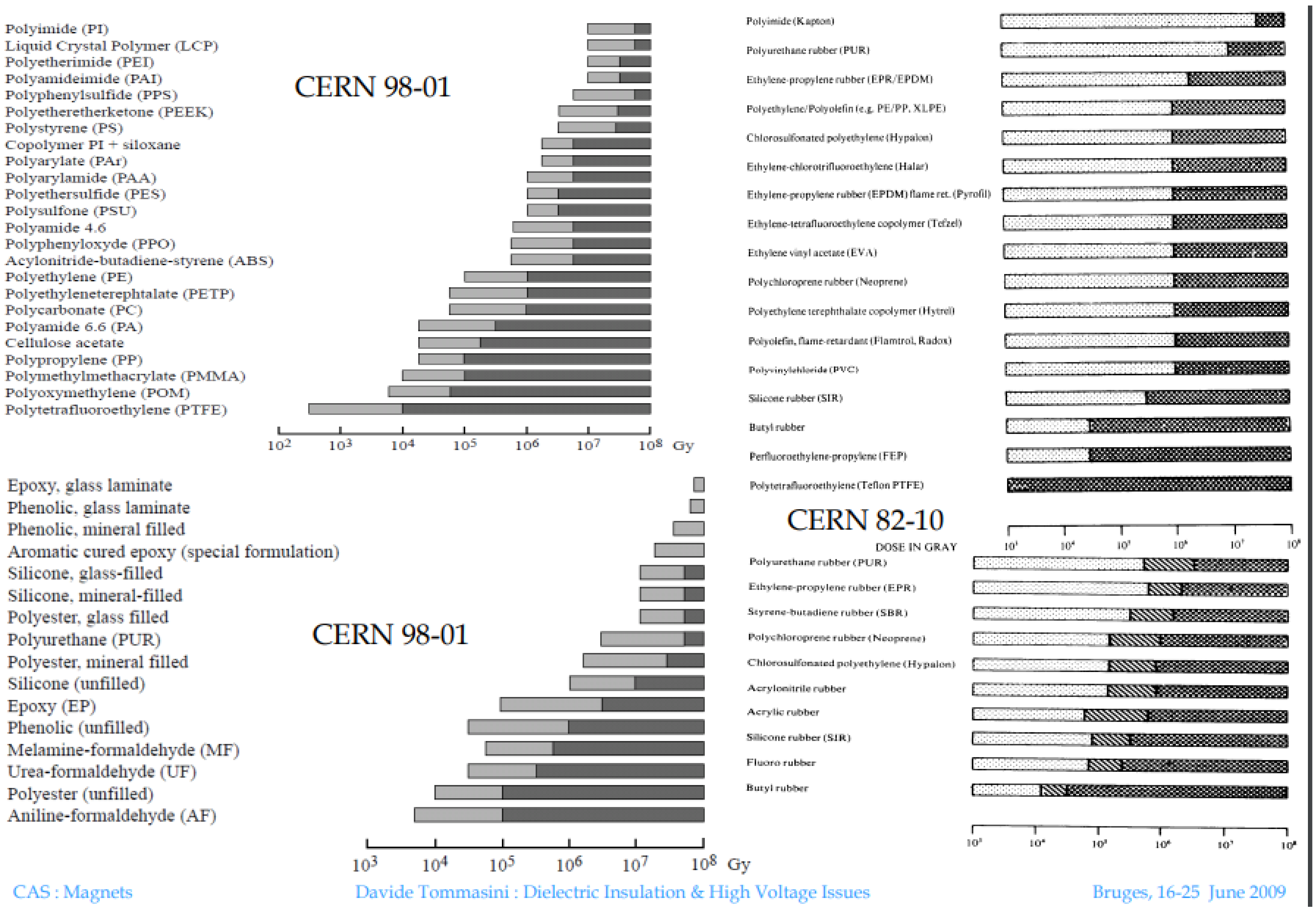
- Polyethylene (PE,LDPE,MDPE,HDPE,XLPE)
- Ethylene-Propylene (EPR)
- Polyimide
- Polyetheretherketone (PEEK)
- Epoxy, phenolic, silicon, polyester resins

Composites

- Kevlar
- Carbon
- Fiber-glass
- Mica

CAS : Magnets   Davide Tommasini : Dielectric Insulation & High Voltage Issues   Bruges, 16-25 June 2009

Radiation compilation data



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