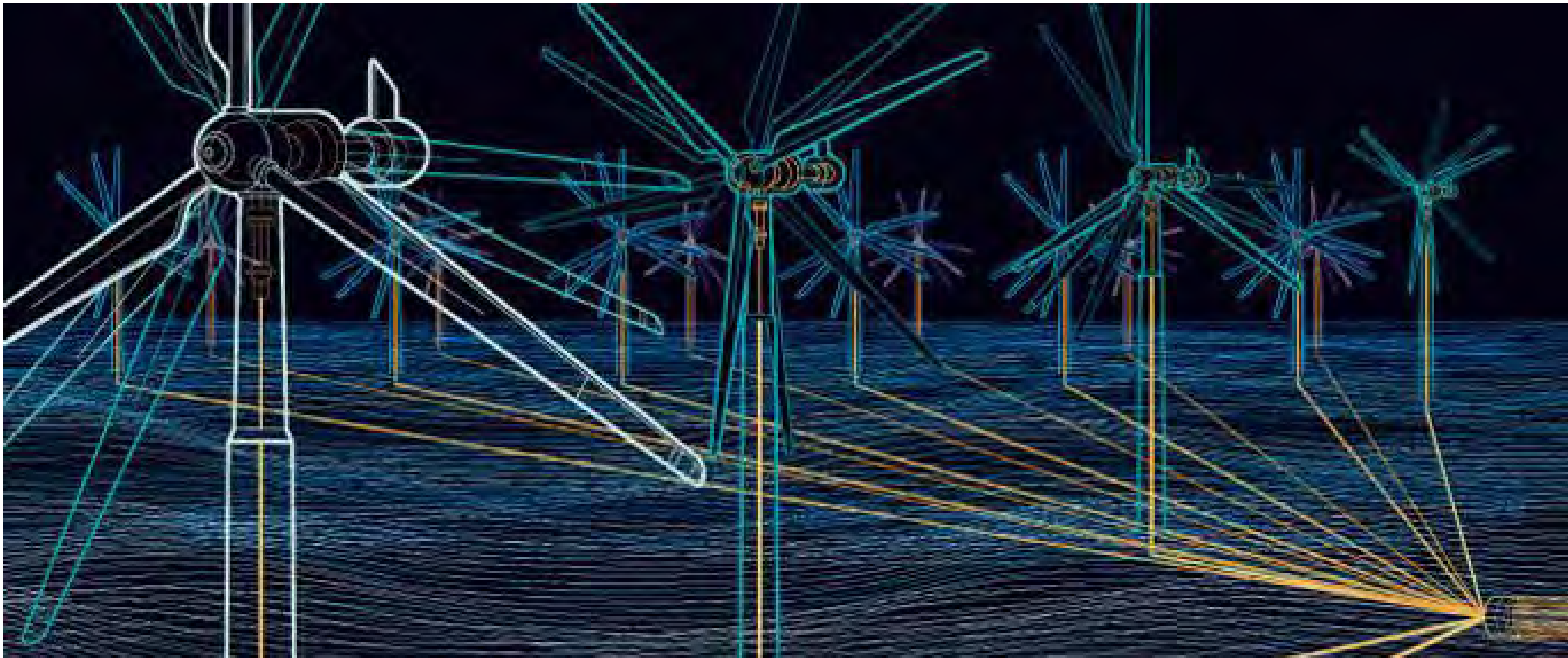
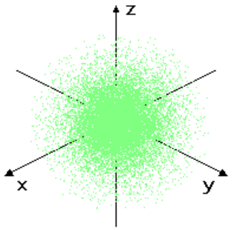


Marc Jeroense, ABB, ICC, March 23, 2010

Education Session
HVDC, embrace or reject?

The journey

- From a global perspective to the smallest entities



Orbital s ($\ell = 0$, $m_\ell = 0$)

Content

- Why HVDC?
- Types of cables
  - MI
  - Extruded
  - Other
- Electric field
  - AC
  - DC
  - Space charge – what is it?
  - Space charge – how do you measure it?
- Accessories
  - Joints (flexible, stiff)
  - Termination
- Qualification
  - Recommendations (CIGRÉ)
  - Type test
  - Pre-qualification test

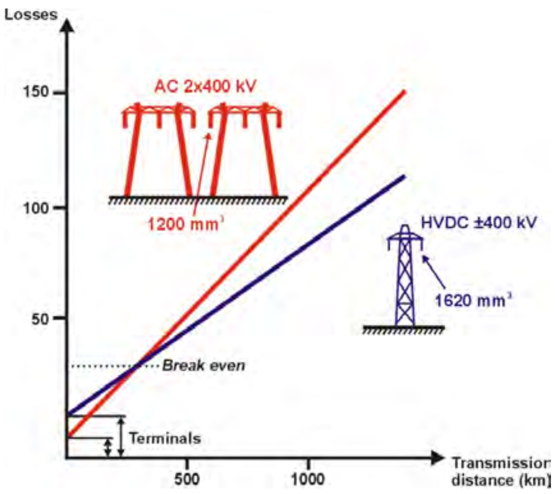
Why HVDC?

- Traditional applications (Classic and HVDC Light)
  - Sub sea transmission
  - Long distance transmission
  - Asynchronous interconnections

- New applications (HVDC Light)
  - …
  - …
  - … (next slide)

Why HVDC?
New HVDC applications

- Underground transmission



- Oil & Gas

- Offshore Wind power

Why HVDC?
The issue of renewables

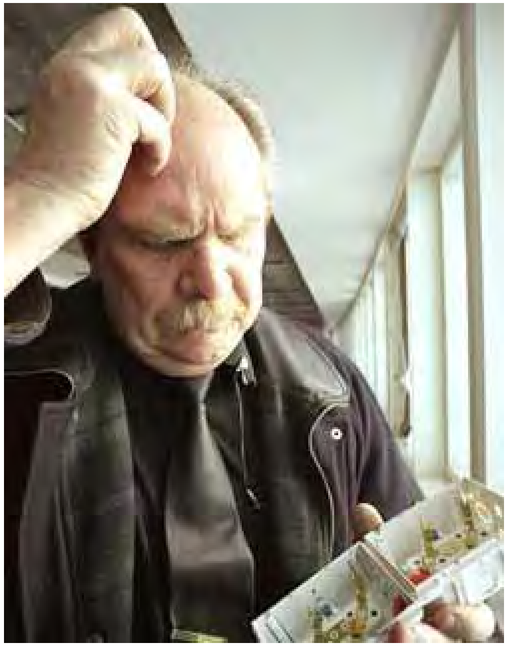
- Increase the use of renewables, with for instance

Hydro power

Solar power

Why HVDC?
The issue of renewables

- There is a problem though…



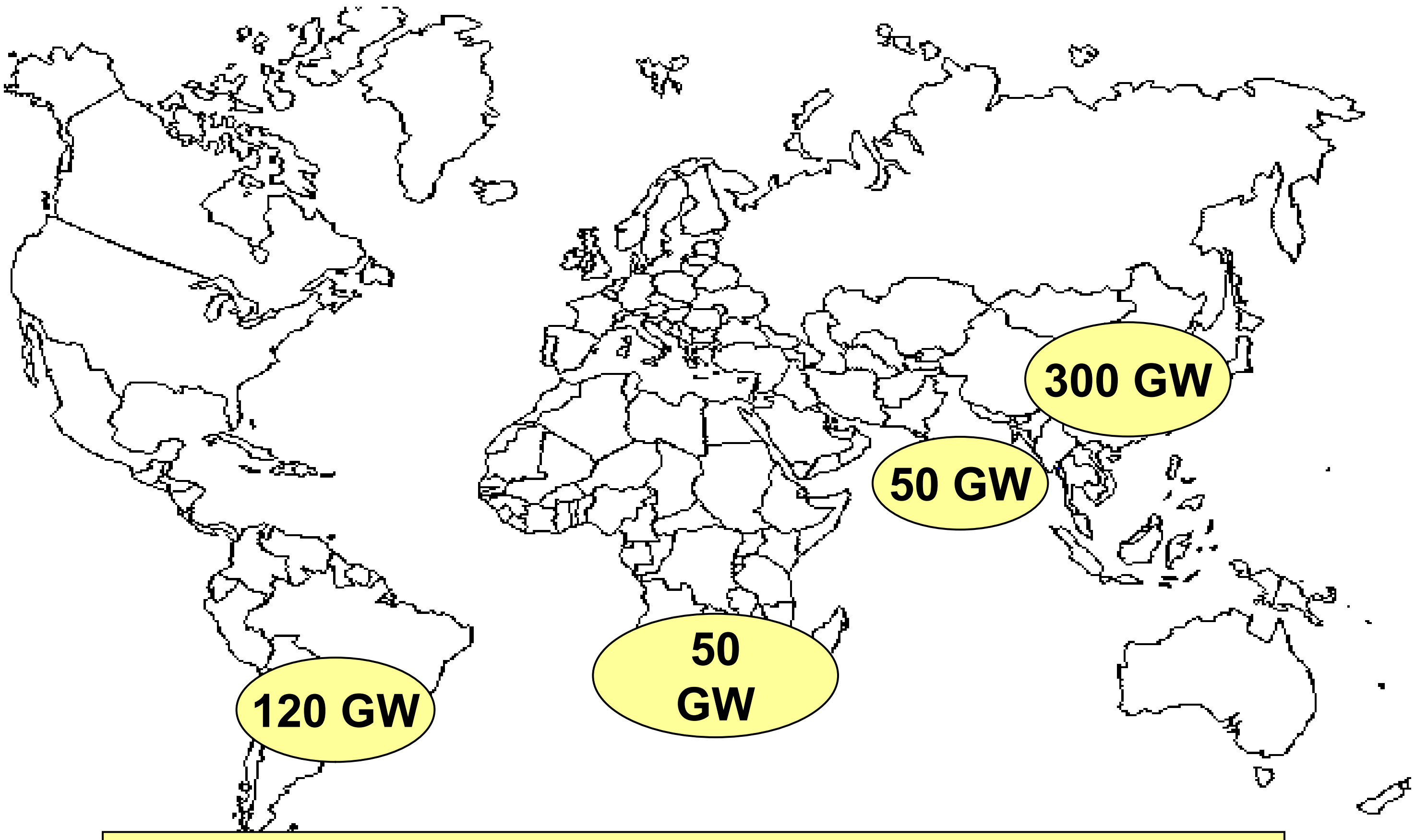
Why HVDC?
The issue of renewables

- The renewable energy sources tend to be located far away from the areas of consumption

Losses increase as per distance!

Why HVDC?

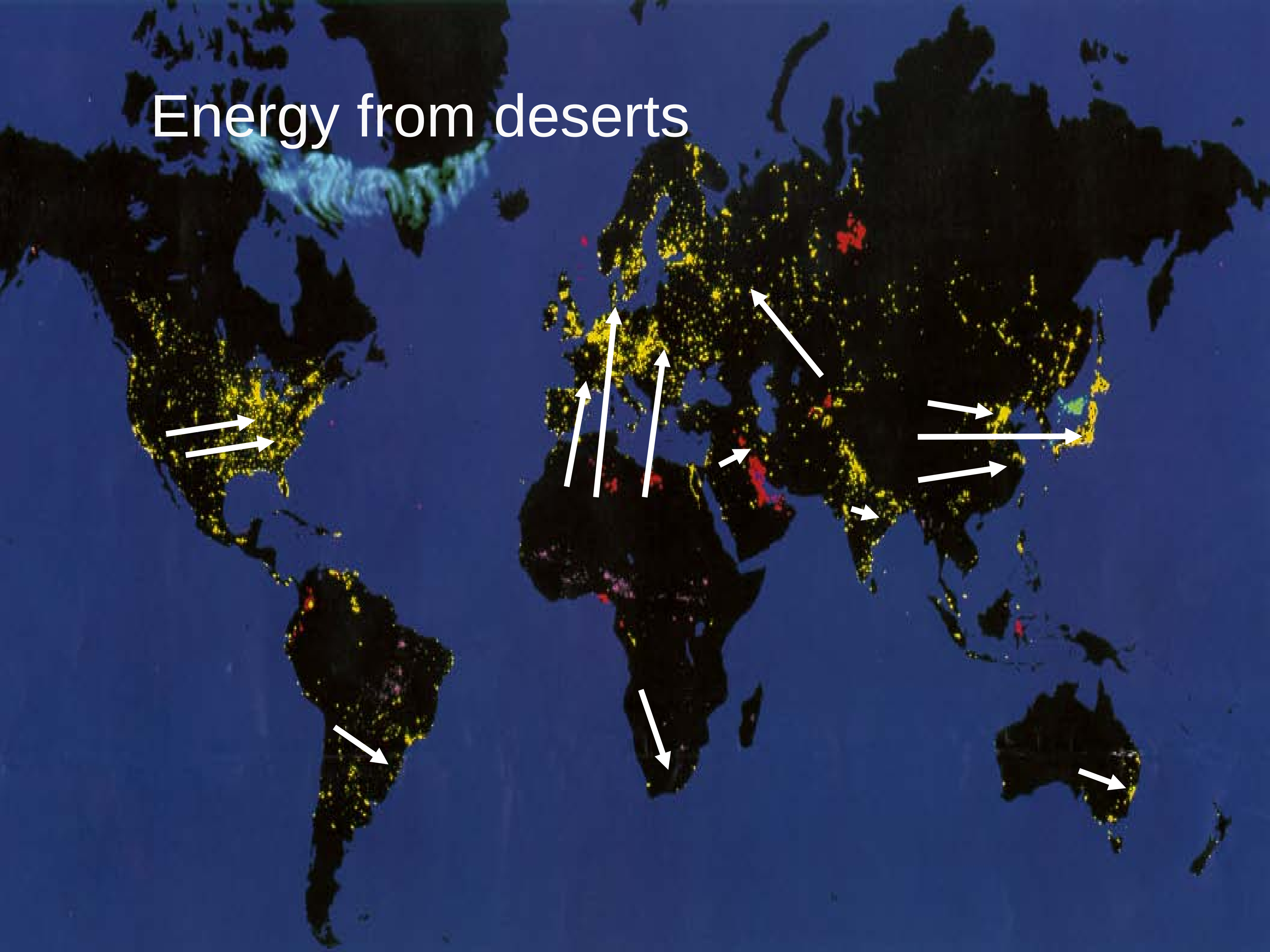
- Remote hydro power resources



Totally about 500 GW

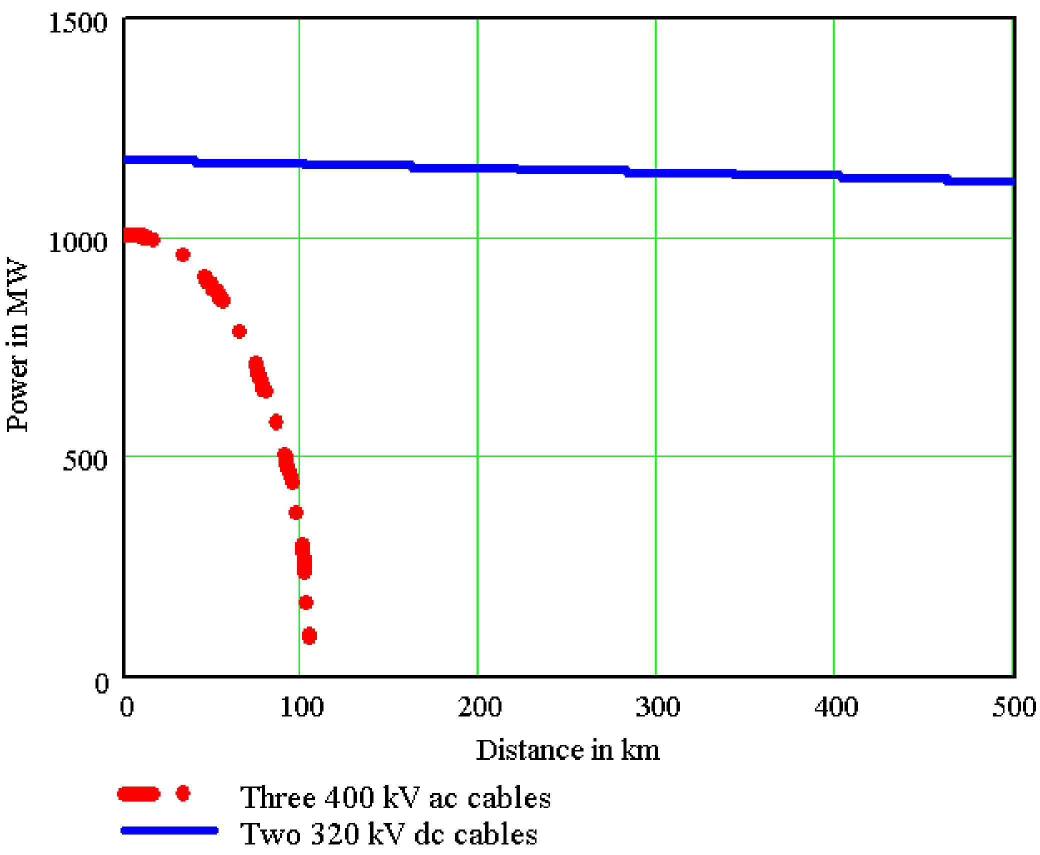
Transmission 2000 – 3000 km

Energy from deserts

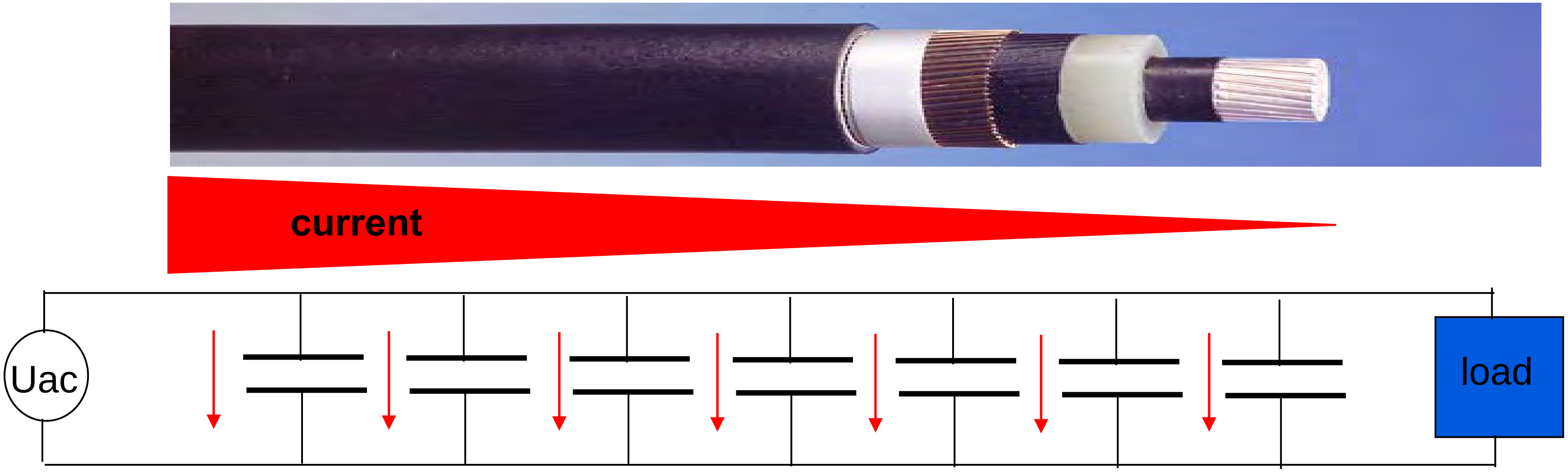


Why HVDC?

- Why not HVAC?
  - Charging currents (cable acts as a capacitance)

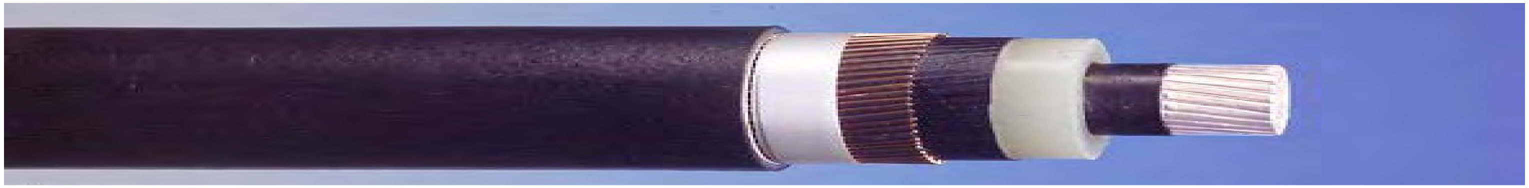


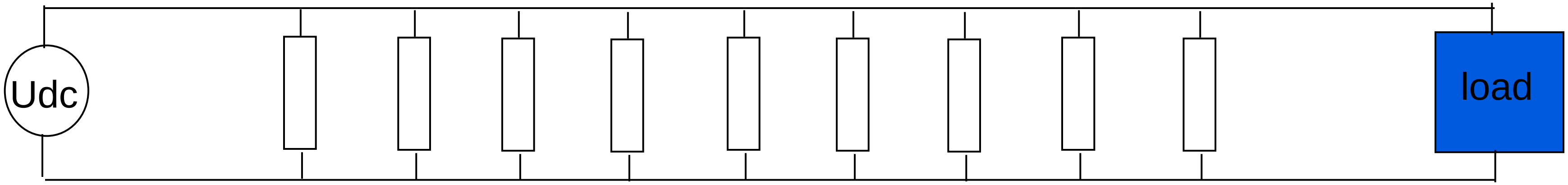
Why HVDC?



- Maximum length of ac cables
  - The longer the cable, the more current the cable asks for itself.
  - At a certain length the this cable current heats the cable to its maximum temperature
  - At 10-20% reduction of current, economicaly uninteresting → critical length

No maximum length for DC cable





No charging current! → **No critical length!**

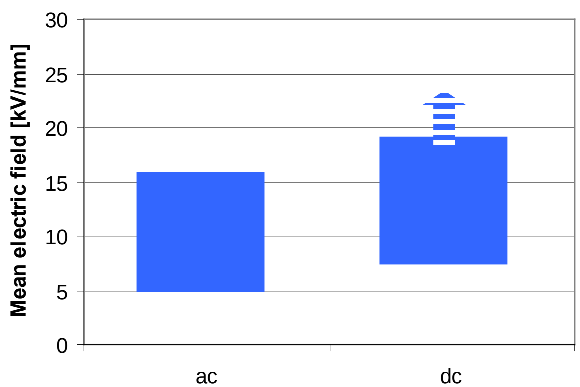
… and lower losses

AC cables

- Ohmic Losses in conductor
- Induced losses in conductor
- Induced losses in sheath
- Induced losses in armouring
- Induced losses in neighbouring cables
- Cable current due to length

DC cables

- Ohmic Losses in conductor
- -
- -
- -
- -
- -



AC DC

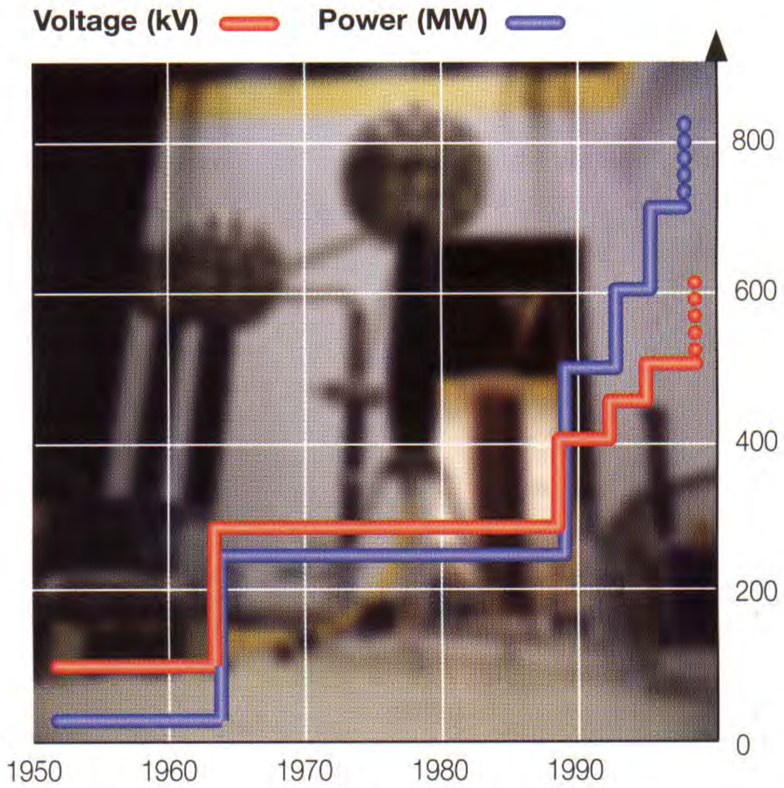
Types of HVDC cables

- **MI** – Mass Impregnated paper insulation
  - Maximum conductor temperature 55°C
  - Maximum voltage commercially available 500 kV

- **Extruded**, like HVDC Light cables
  - Maximum conductor temperature at least 70°C
  - Maximum voltage commercially available 320 kV

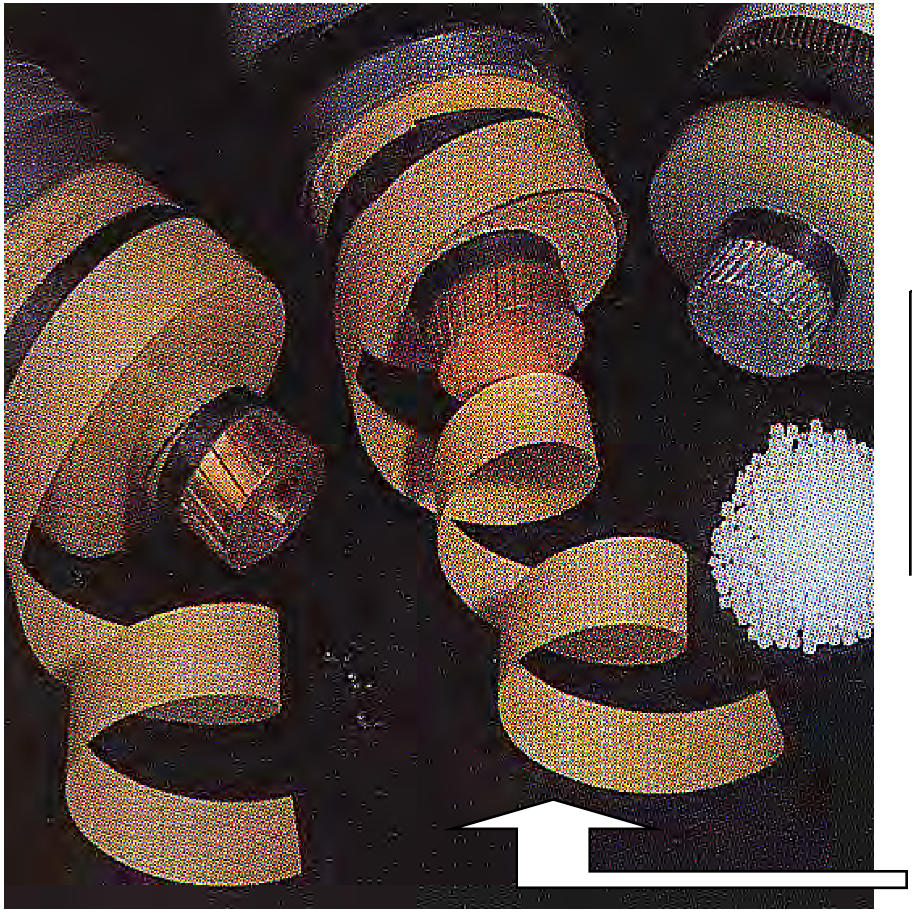
- Less usual: oil pressurised cables for HVDC

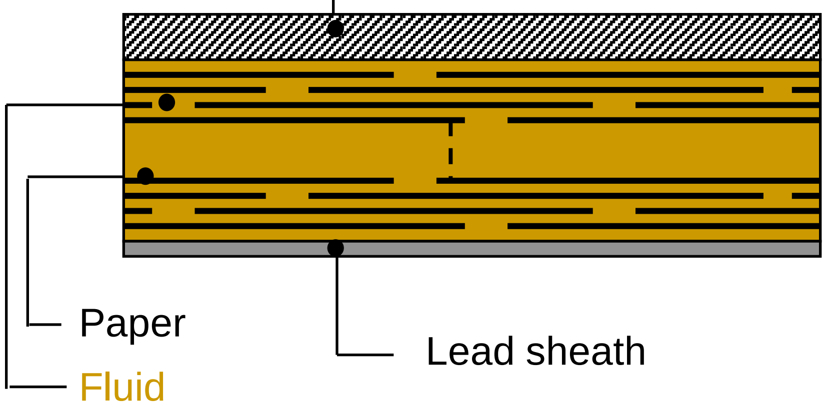
MI cable development history



HVDC cable development

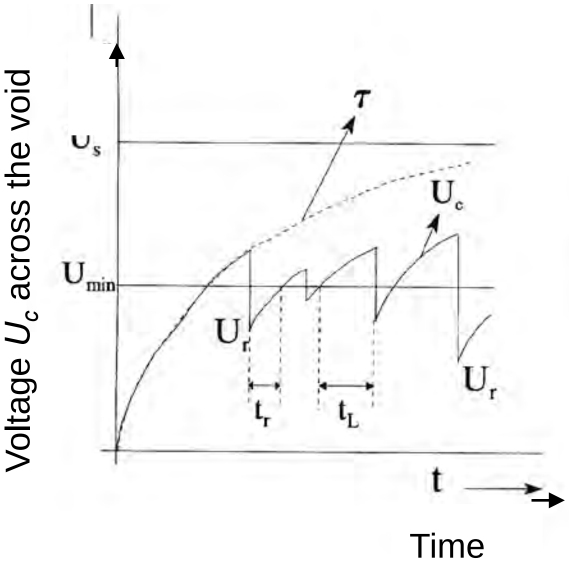
MI Cable

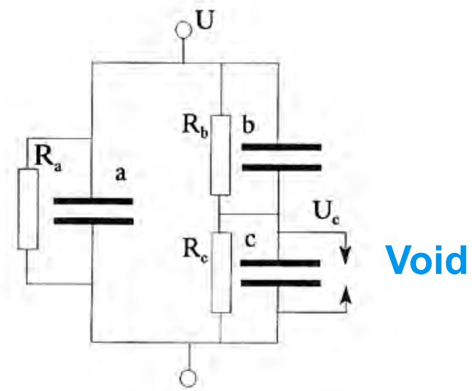




HVDC **M**ass **I**mpregnated **N**on-**D**raining cable

MI Cable
Partial Discharges at DC - one void



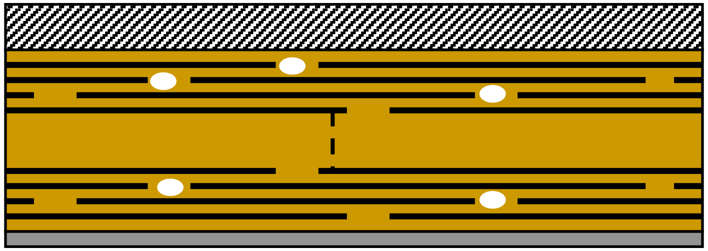


$$n \approx \frac{1}{\tau} \frac{U_s}{U_{min} - U_r} = \frac{1}{\tau} \frac{U_s}{U_{min}(1-\alpha)}$$

The repetition rate *n* of the void depends on the:

- asymptotic voltage across U_s the void
- time constant τ
- minimum breakdown voltage U_{min}
- residual voltage U_r ($\alpha = U_r / U_{min}$)

MI Cable
Partial Discharges at DC - many voids



$$n \approx \frac{1}{\tau} \frac{U_s}{U_{min}(1-\alpha)}$$

One void

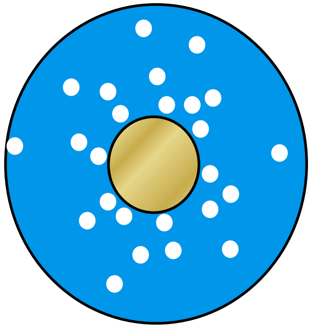
Voids in

- butt-gaps
- between paper layers
- inside paper

$$n \approx \sum_r \frac{1}{\tau_r} \frac{E_r}{U_{min,r}(1-\alpha_r)} \phi_r$$

Many voids:

Cable

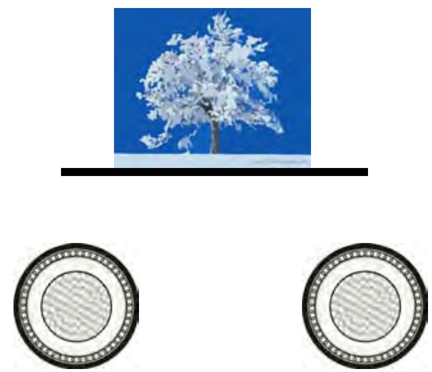


Void distribution: Φ_r

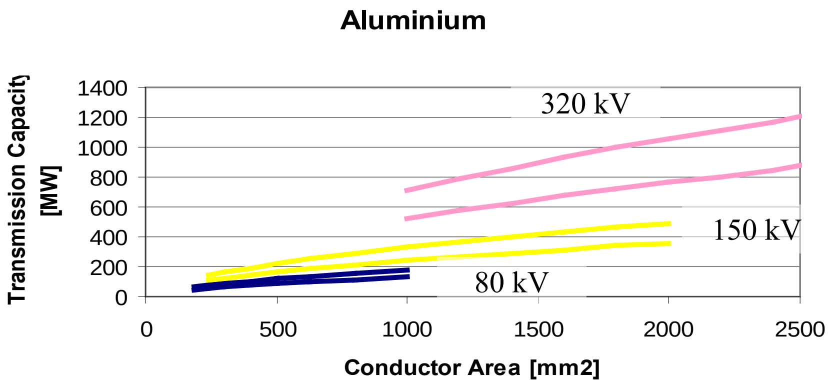
Extruded HVDC cable systems
HVDC Light cable system

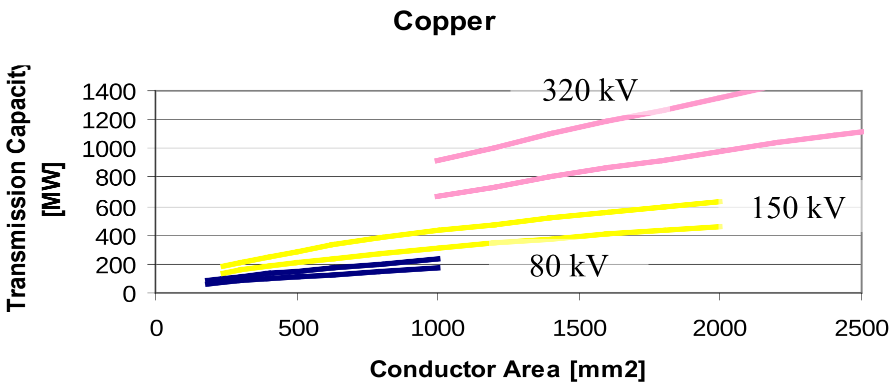
- Commercially available up to 320 kV
- Joint
  - Prefabricated
  - Flexible
- Termination
- Cable
  - DC polymer insulation
  - Copper or aluminium conductor

Extruded HVDC cable system
What power can it transmit?



Extruded HVDC cable system
What power can it transmit?

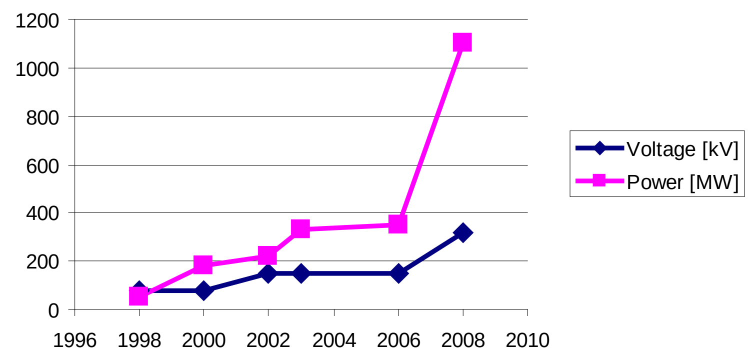




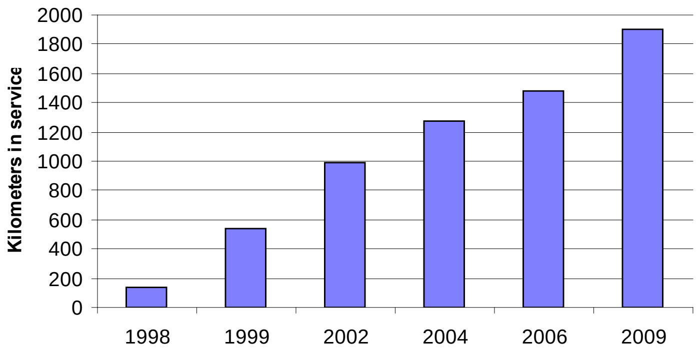
- Transporting power depends on
  - Voltage
  - Conductor area
  - Installation conditions

Extruded HVDC cable system
Qualification

- Extruded HVDC cable systems becoming a mature product
- More than 20 type tests and several long term tests have qualified the cable system on the 80, 150 and 320 kV level



- By the end of 2009 a total of 1903 km HVDC Light cable is in service



Japan has qualified extruded HVDC cable systems up to 500 kV

Extruded HVDC cable system

Applications

Oil & gas

On/Offshore Wind

Bulk transport – sea

Bulk transport – land

Extruded HVDC cable system
Experience and projects

- Oil and gas
  - Troll-A 284 km

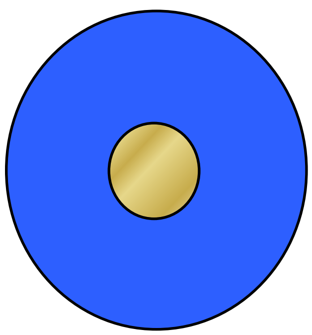
- On/Offshore Wind
  - BorWin 1 421 km
  - GotLight 140 km

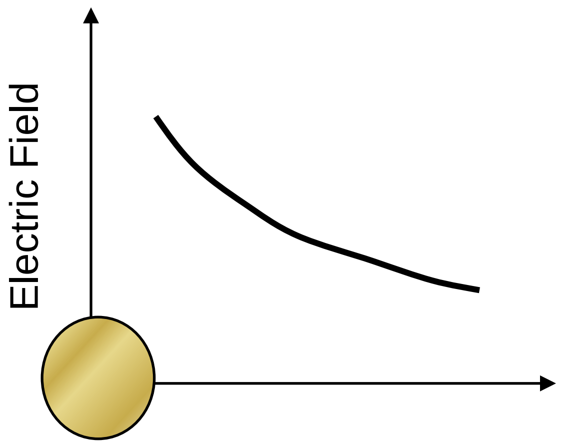
- Bulk transport sea
  - Estlink 212 km
  - Cross Sound 85 km
  - Transbay xx km
  - Hokkaido Island and Honshu Main Land. 45 km
  - EWIP 500 km

- Bulk transport land
  - MurrayLink 360 km
  - DirectLink 390 km

Electric field
AC

- The field distibution depends solely on the permittivity and the geometry of the cable

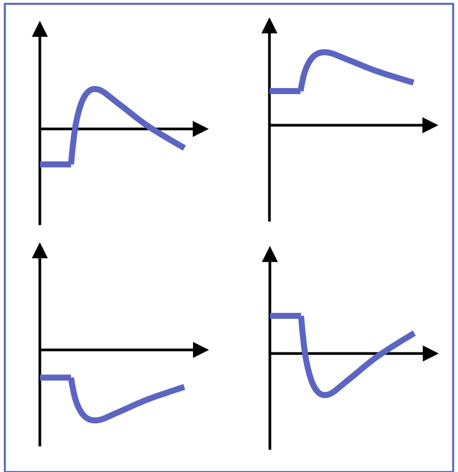




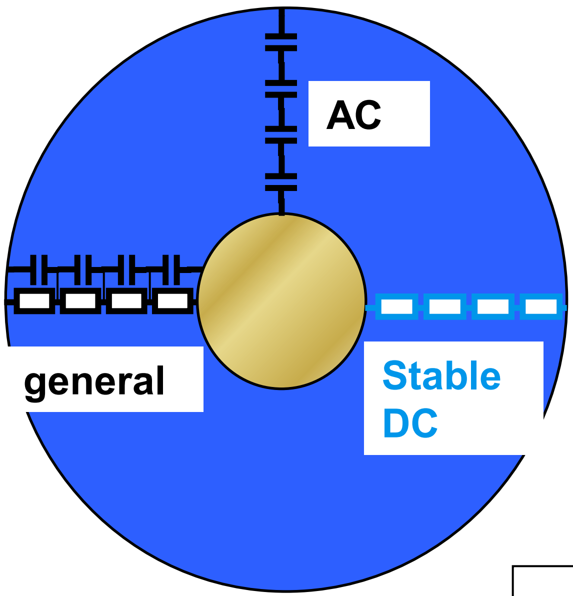
Electric field
DC

- ”What is the electric field?”
  - What do you mean?

- Capacitive field → t=0
- Intermediate (transient) field $0<t<\infty$
- Resistive field → $t=\infty$
- Switching surge fields



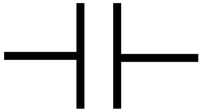
Electric field
Resistive



$$\nabla \cdot \left(\sigma(T,E)\nabla U\right) + \nabla \cdot \left(\frac{\partial}{\partial t}\left(\varepsilon_r \varepsilon_0 \nabla U\right)\right) = 0$$

Stable DC fields

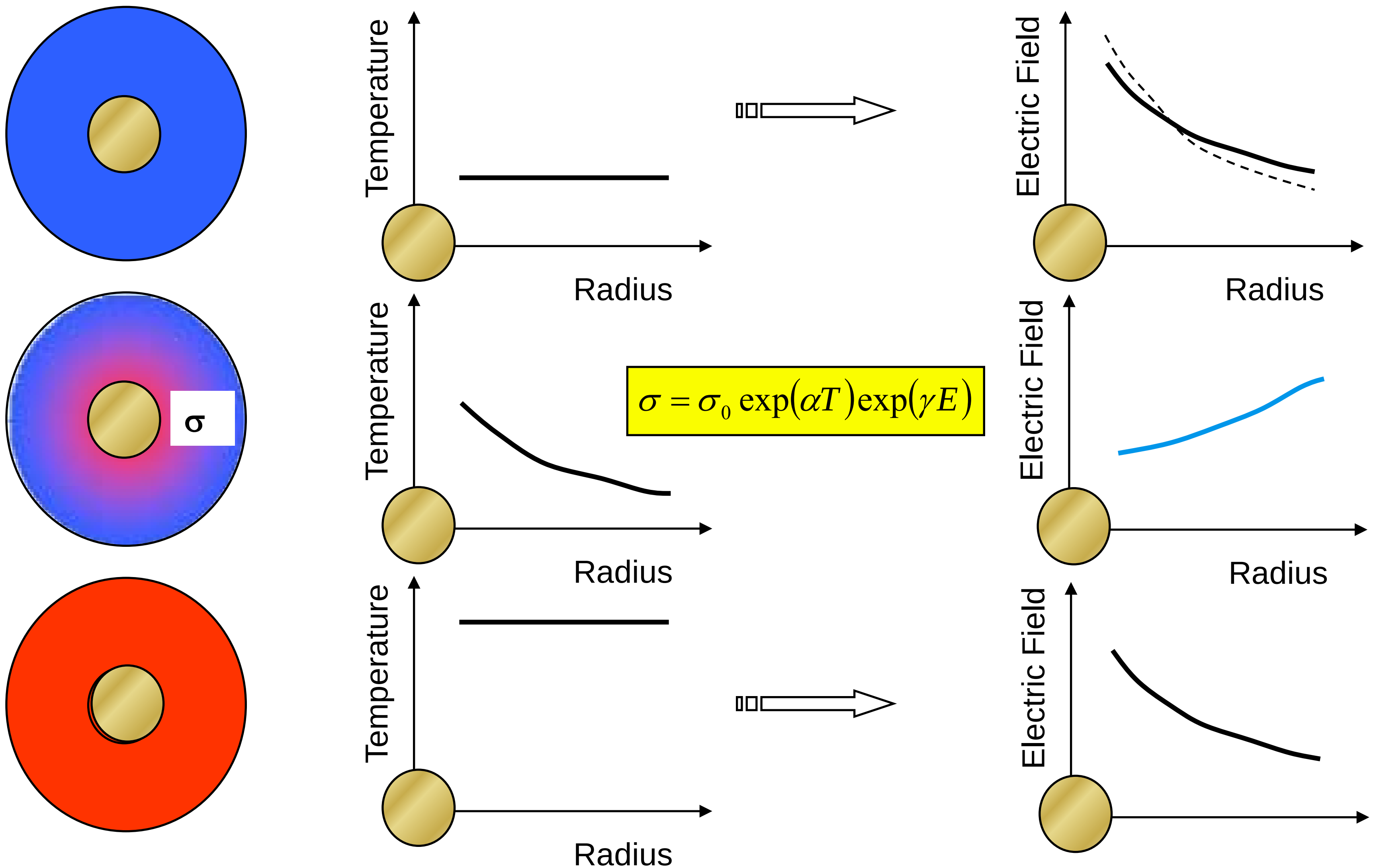
Time-dependent fields
- Changing voltage
- Changing temperature



$$\varepsilon = \text{constant}$$

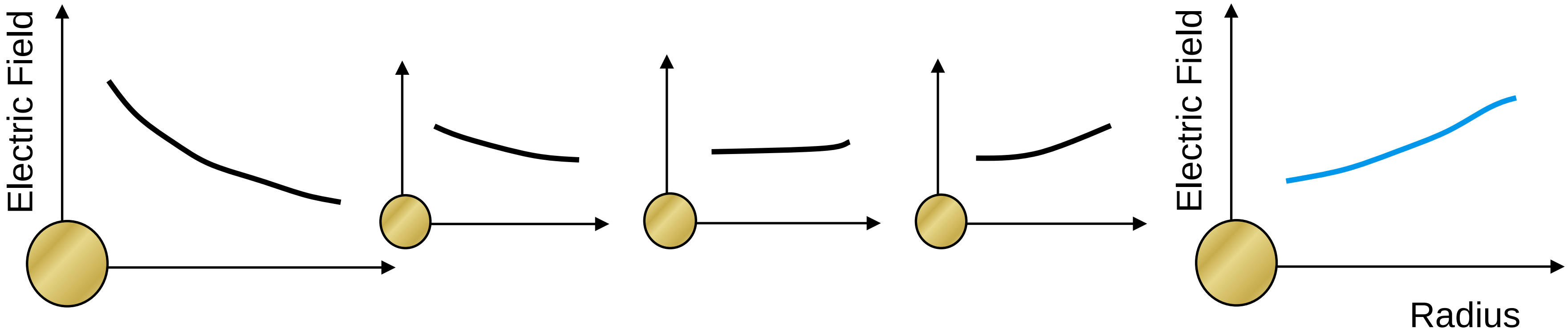
$$\sigma = f\begin{pmatrix}\text{Temperature,} \\ \text{Electric Field}\end{pmatrix}$$

Electric field
Resistive



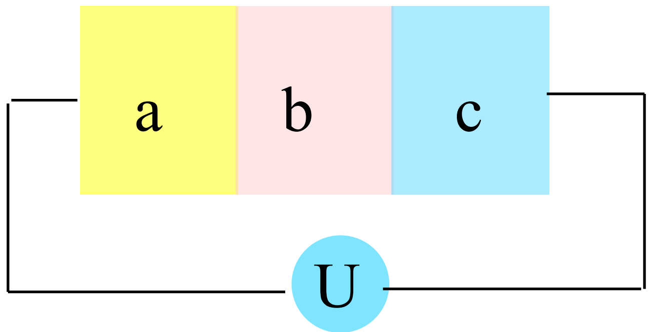
Electric field
Intermediate

- From capacitive to resistive distribution (loaded cable in example)



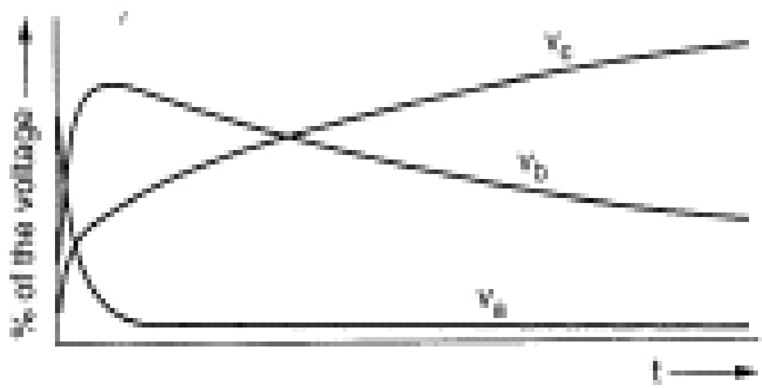
Electric field
Intermediate

- Consider a 3-layer Maxwell capacitor

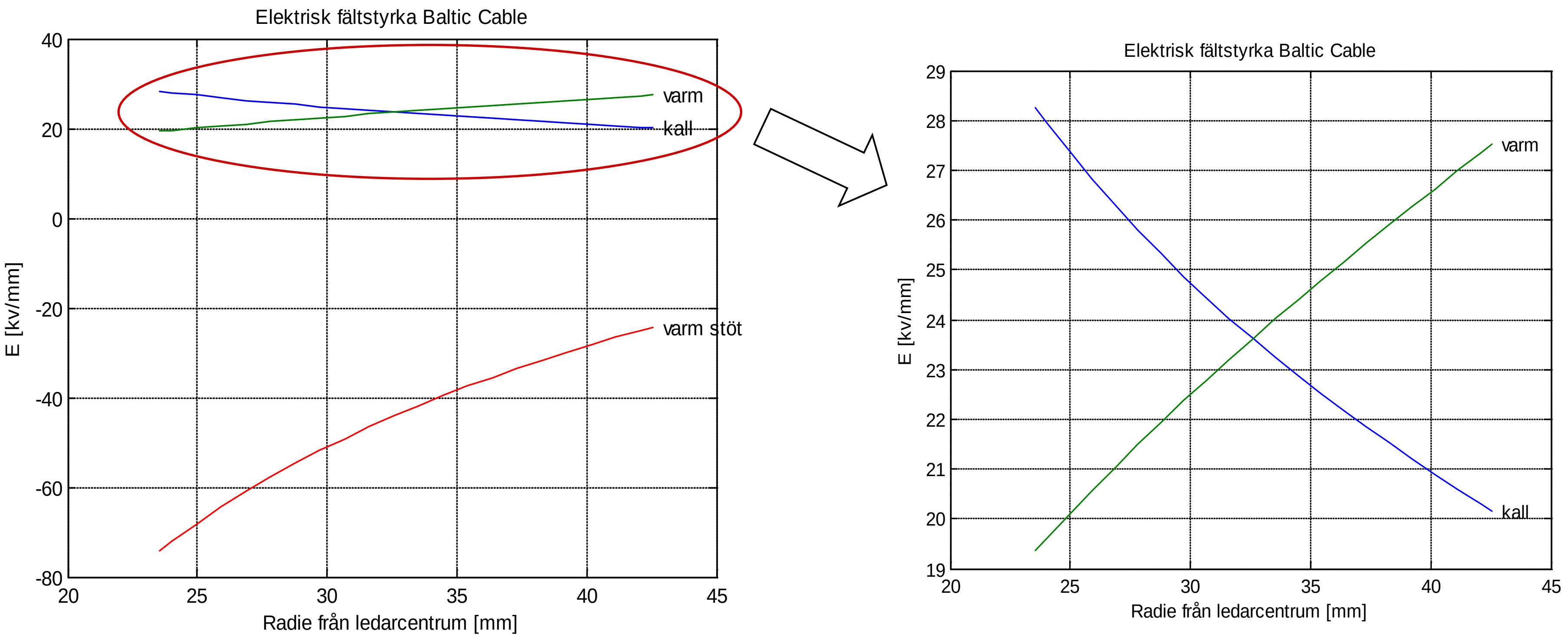


$$\tau = \frac{\varepsilon}{\sigma}$$

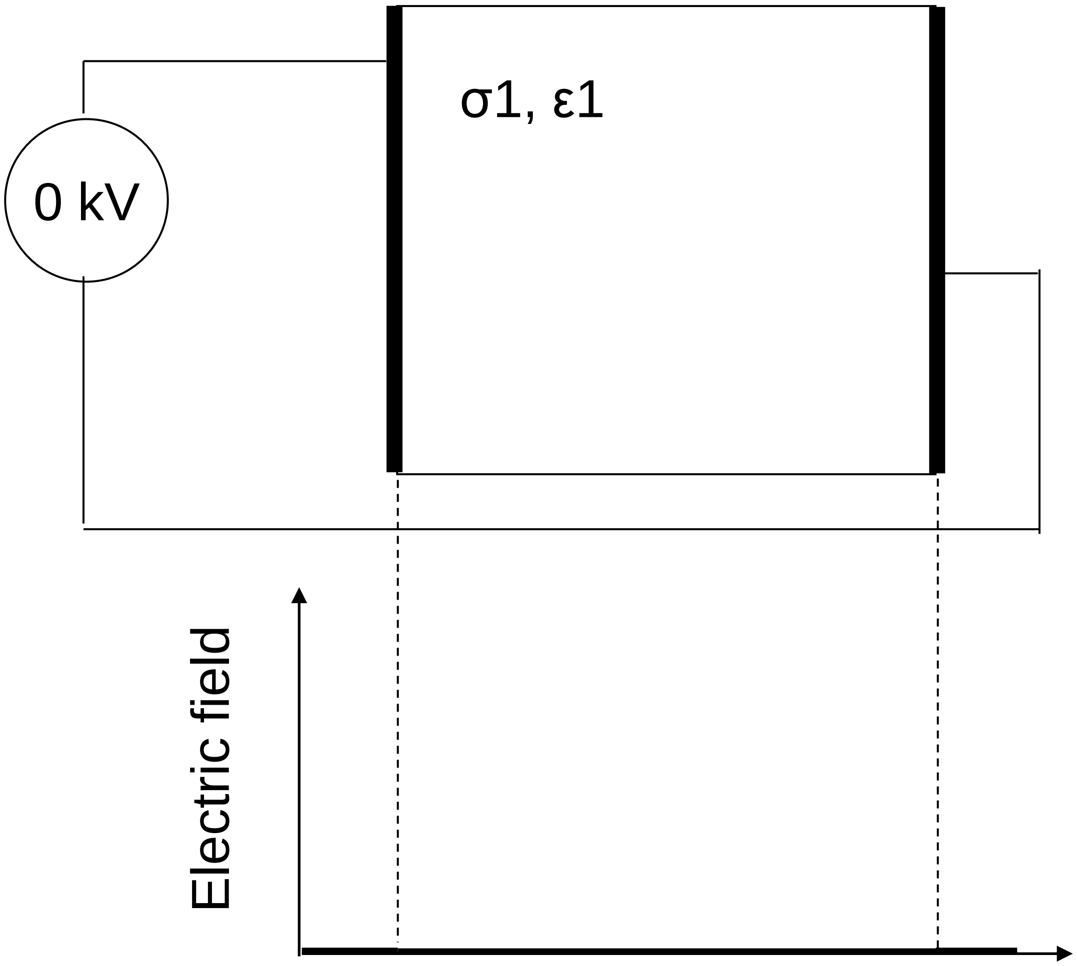
$$\tau_a = 0.5\tau_b = 0.1\tau_c$$



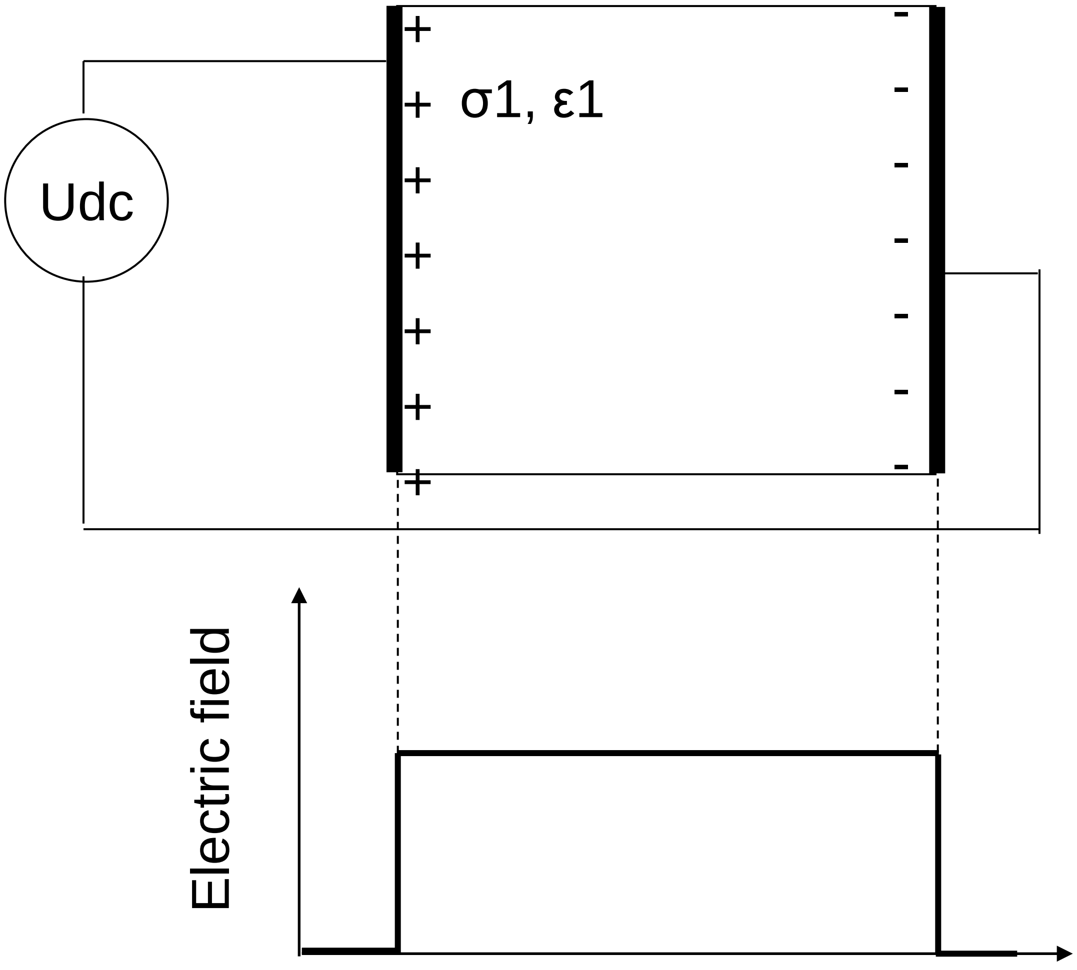
Electric field
Resisive and surge



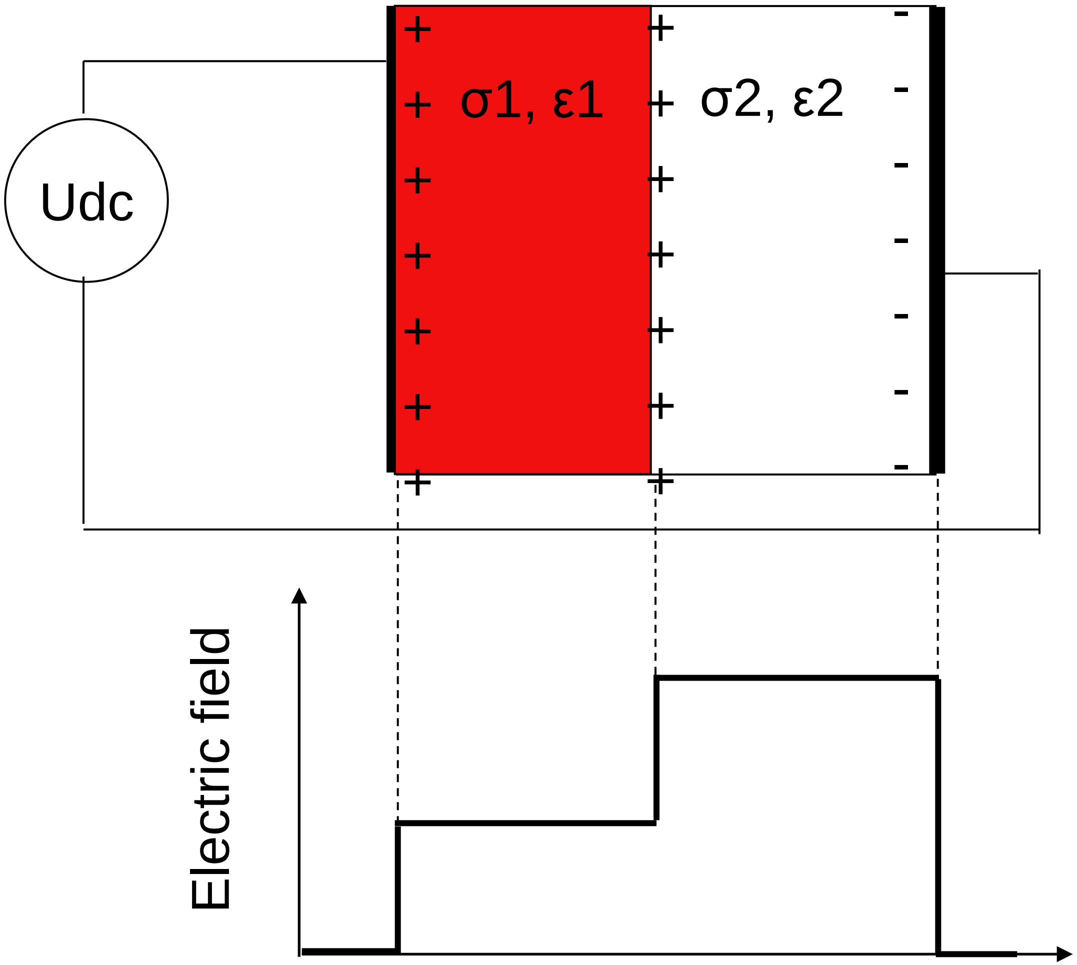
Electric field
Space charge



Electric field
Space charge

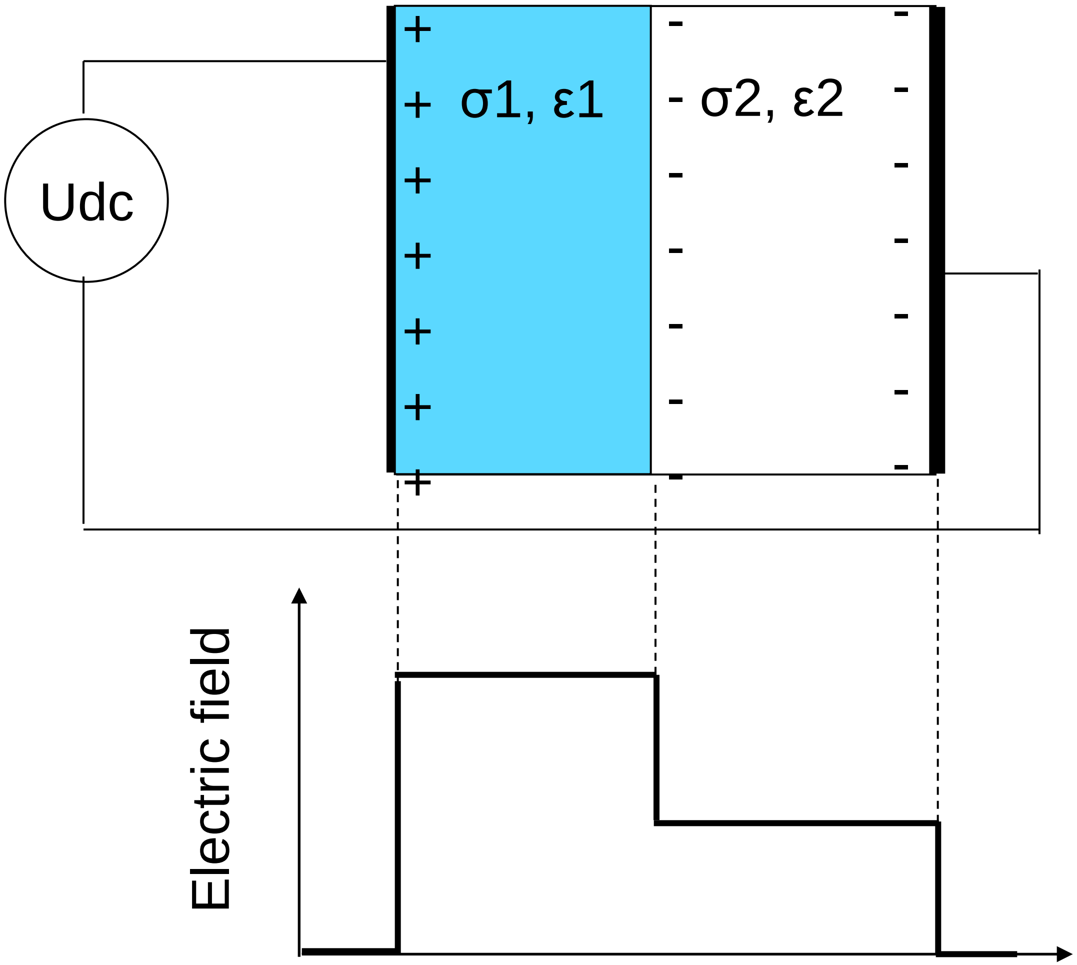


Electric field
Space charge



σ1>σ2

Electric field
Space charge



σ1<σ2

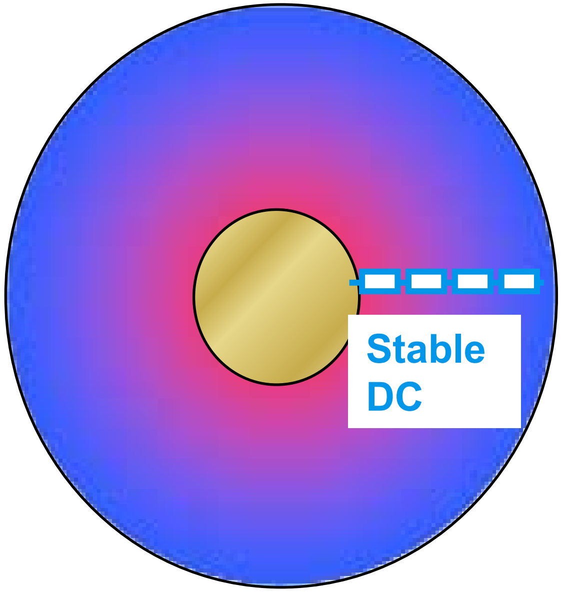
Electric field
Space charge

- Which brings us to the conclusion that space charge must exist whenever there exists a change in dielectric properties

- More exact, space charge evolves when $\nabla \frac{\sigma}{\varepsilon} \neq 0$

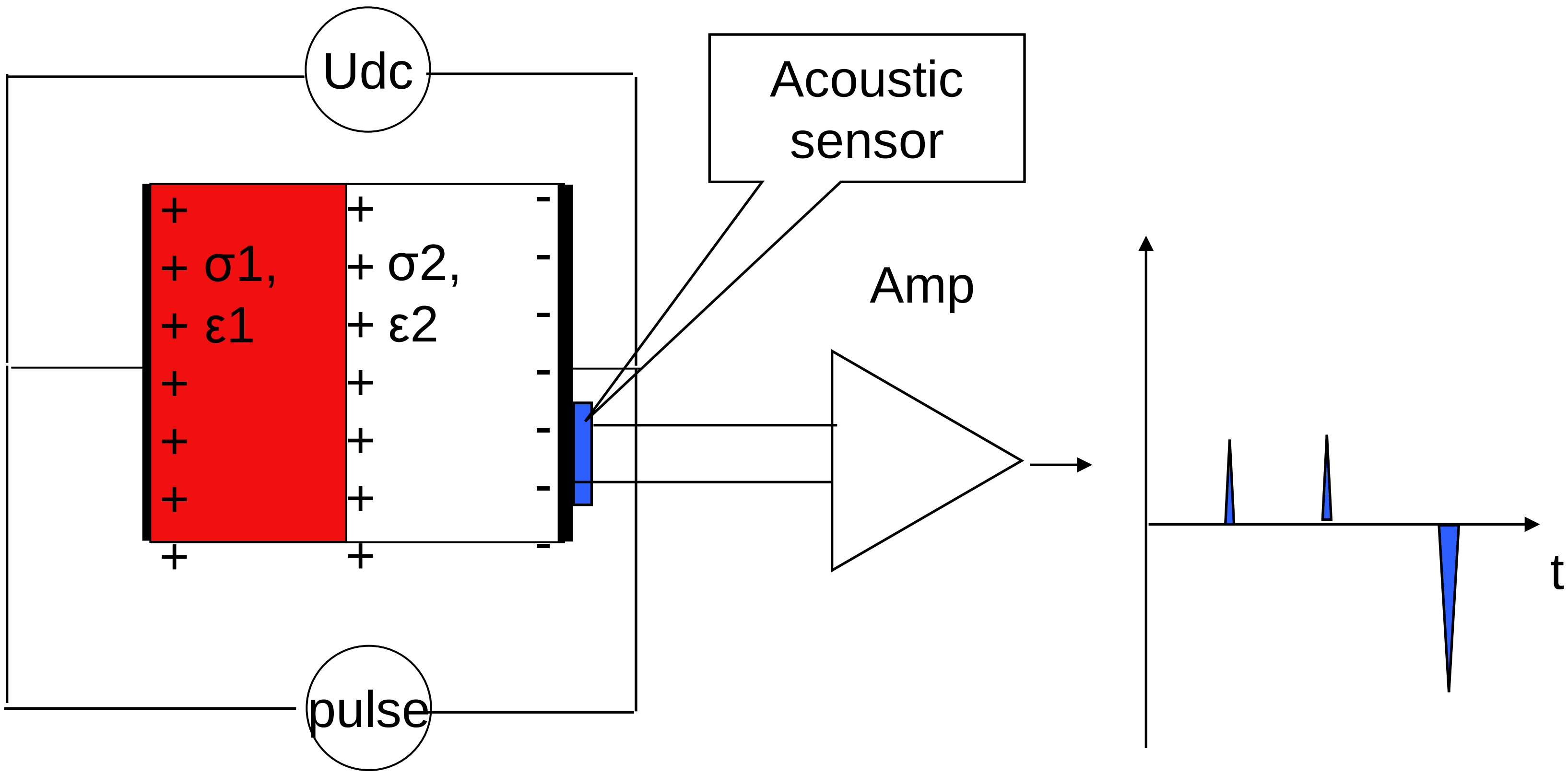
Electric field
Space charge

- Back to our loaded dc cable with a temperature drop across the inuslation
  - As the conductovity is temperature dependent
  - And as the temperature is not constant along te radius
  - This must mean that $\nabla \frac{\sigma}{\varepsilon} \neq 0$
  - Which in its turn means that we have space charge inside the cable



Electric field
Space charge

- How do you measure it?



Accessories
Joints and terminations

- Joints
  - Factory joints
  - Field joints
  - Transition joints
  - Repair joints

  - One can go outside the green blocks, but it is not usual

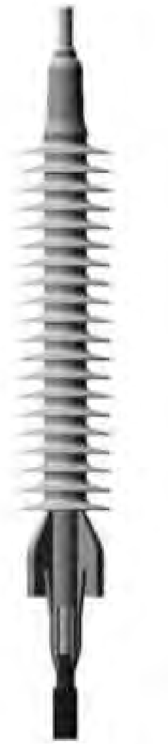
	Sea	
	Flexible	Stiff
Factory joints		
Field joints		
Transition joints		
Repair joints		

	Land	
	Flexible	Stiff
Factory joints	NA	NA
Field joints		
Transition joints		
Repair joints		

Accessories (HVDC Light example)
Joints and terminations

80 kV

150 kV



320 kV

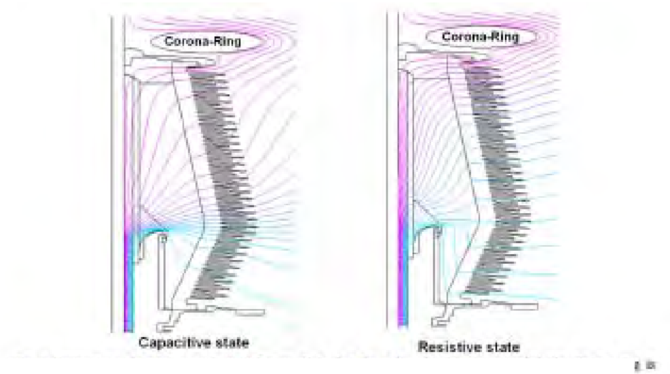
80 kV

150 kV

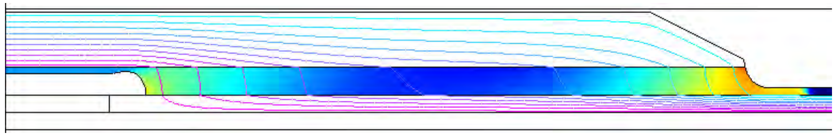
320 kV

Accessories
Calculations

- The basic theory as explained for the cable previously holds for the more complex cases like terminations

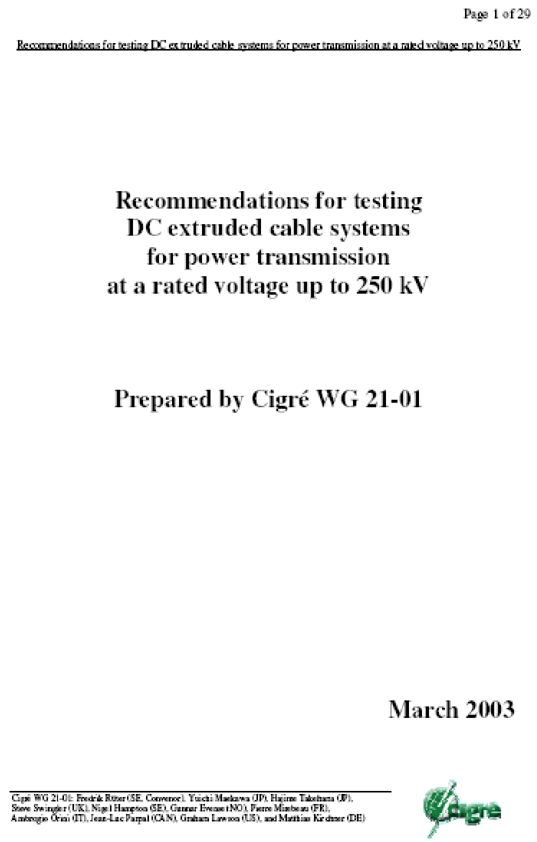


- …and joints



Qualification

- CIGRÉ Brochure 219
  - ”Recommendations for testing DC extruded cable systems for power transmission at a rated voltage up to 250 kV”
  - February 2003
- Now: WG B1.32
  - ”Recommendations for testing HVDC extruded cable systems for power transmission at a rated voltage up to 500 kV”
  - Ready 2011



Page 1 of 29

Recommendations for testing DC extruded cable systems for power transmission at a rated voltage up to 250 kV

Recommendations for testing
DC extruded cable systems
for power transmission
at a rated voltage up to 250 kV

Prepared by Cigré WG 21-01

March 2003

Cigré WG 21-01: Fredrik Ritter (SE, Convenor), Yuichi Maekawa (JP), Hajime Takehana (JP), Steve Swingler (UK), Nigel Hampton (SE), Gunnar Evenset (NO), Pierre Mirebeau (FR), Ambrogio Orini (IT), Jean-Luc Parpal (CAN), Graham Lawson (US), and Matthias Kirchner (DE)

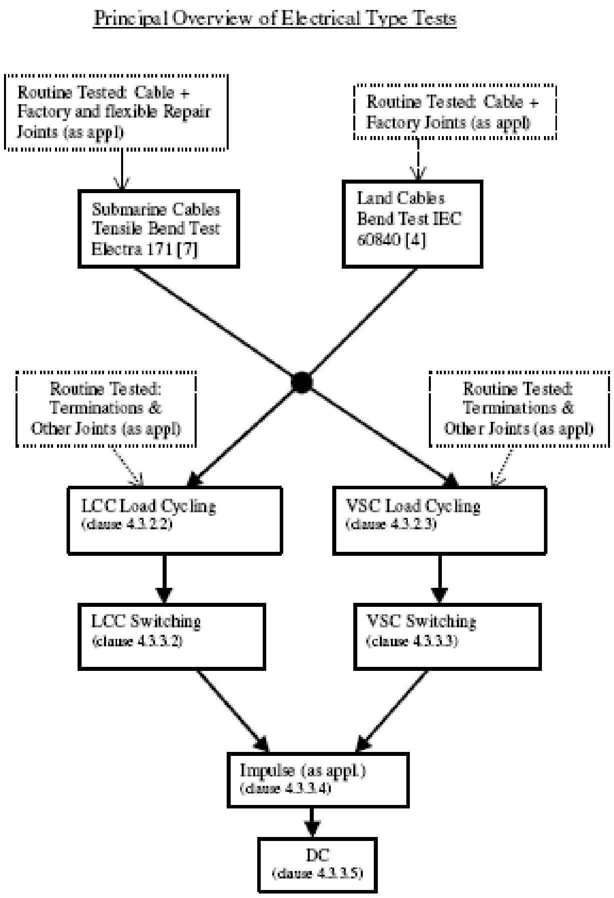
Qualification
CIGRE

- A document for paper insulated HVDC cables

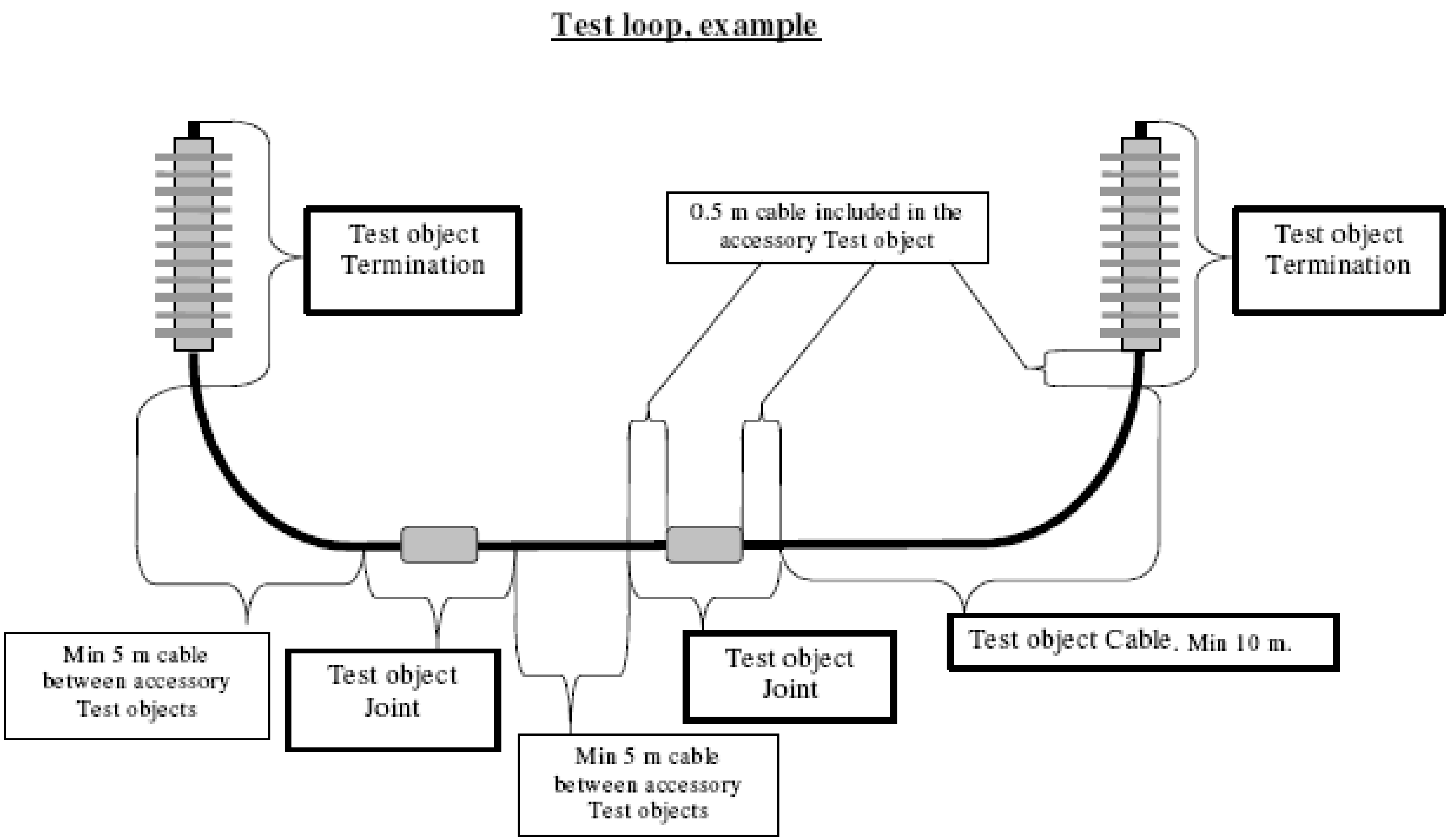
- A document for extruded cable systems

Prequalification Test	Test made before supplying on a general commercial basis a type of cable system covered by this recommendation in order to demonstrate satisfactory long-term performance of the complete cable system.	Once
Type Tests	Tests made on cables and accessories before supplying on a general commercial basis a type of cable system covered by this recommendation to verify the properties of a cable system prior to supplying that particular system.	More than once

Qualification
Scheme for Type Testing

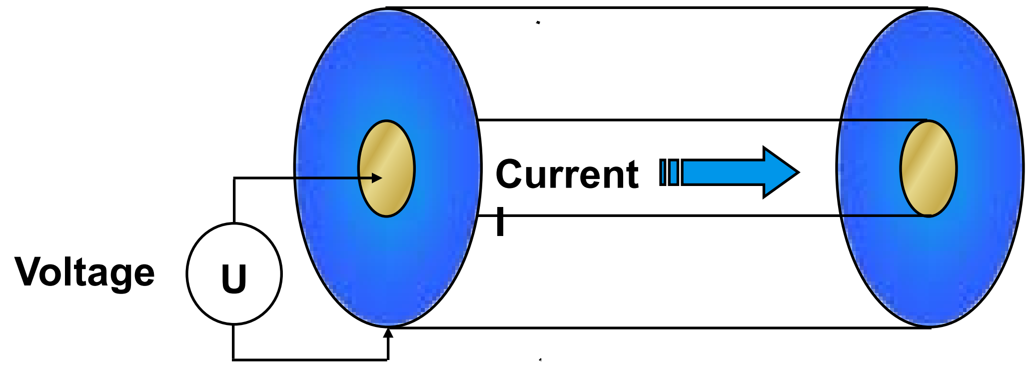


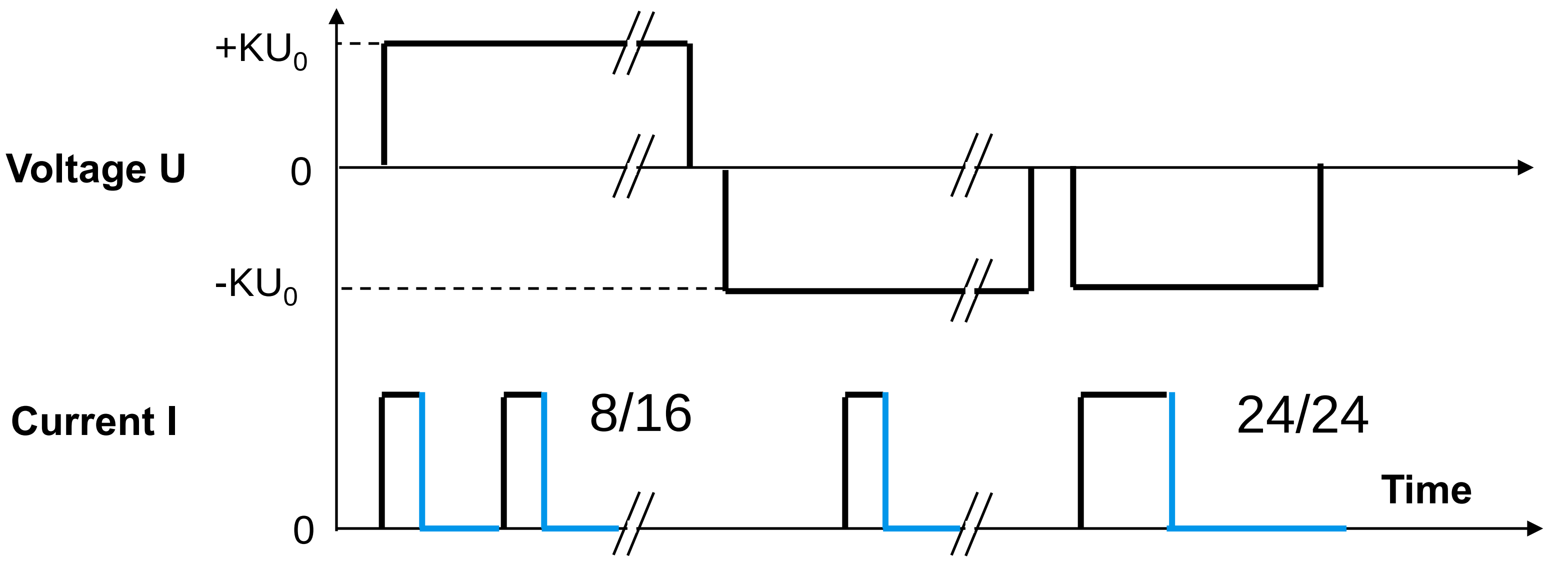
Qualification
Scheme for Type Testing



Qualification
Type Testing

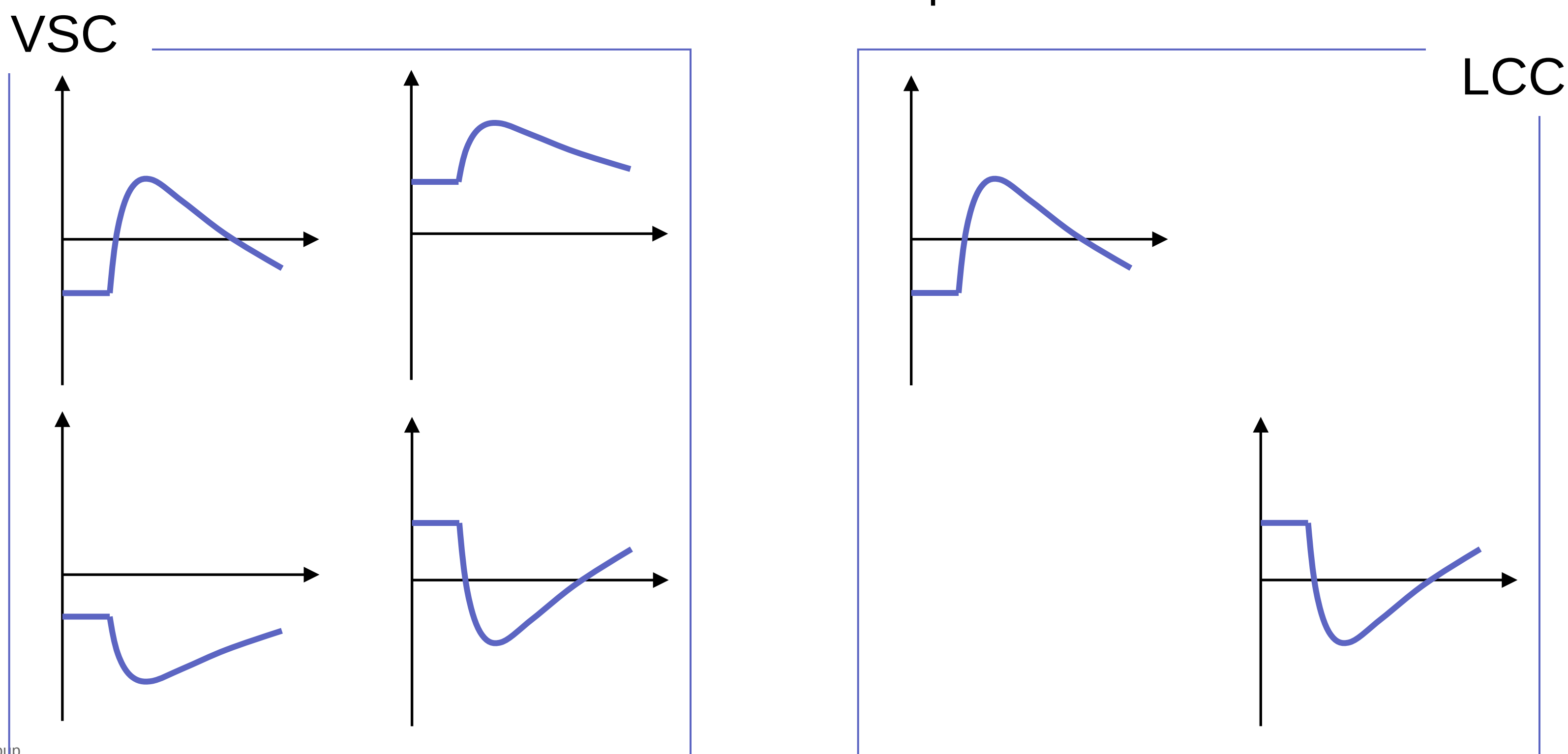
Load Cycle Test





Qualification
Type Testing

- **Superimposed Switching Surge Withstand Test**
  - ”4x10”
  - Superimposed Lightning Surge Withstand test *only* if the terminaton is located – unprotected – outisde



Long Term Testing

Voltage commutated converter VSC

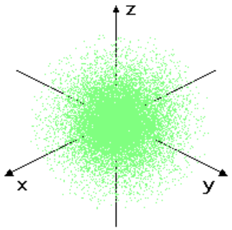
	LC	LC	HL	HL	ZL	LC	LC	S/IMP
Days	40	40	40	40	120	40	40	BIL
Voltage (U_0)	+ 1.45	- 1.45	+ 1.45	- 1.45	- 1.45	+ 1.45	- 1.45	System Design
Total days	40	80	120	160	280	320	360	

LC = Load Cycle HL = High Load PR = Polarity Reversal ZL = Zero Load

S/IMP = Superimposed Impulse Test

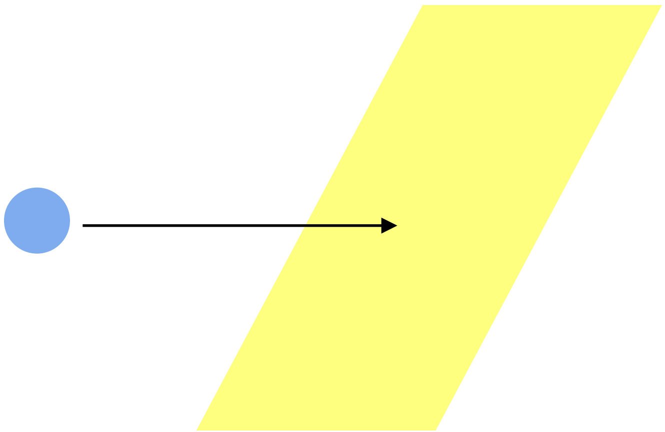
… a last thing
I promised you

- From a global perspective to the smallest entities



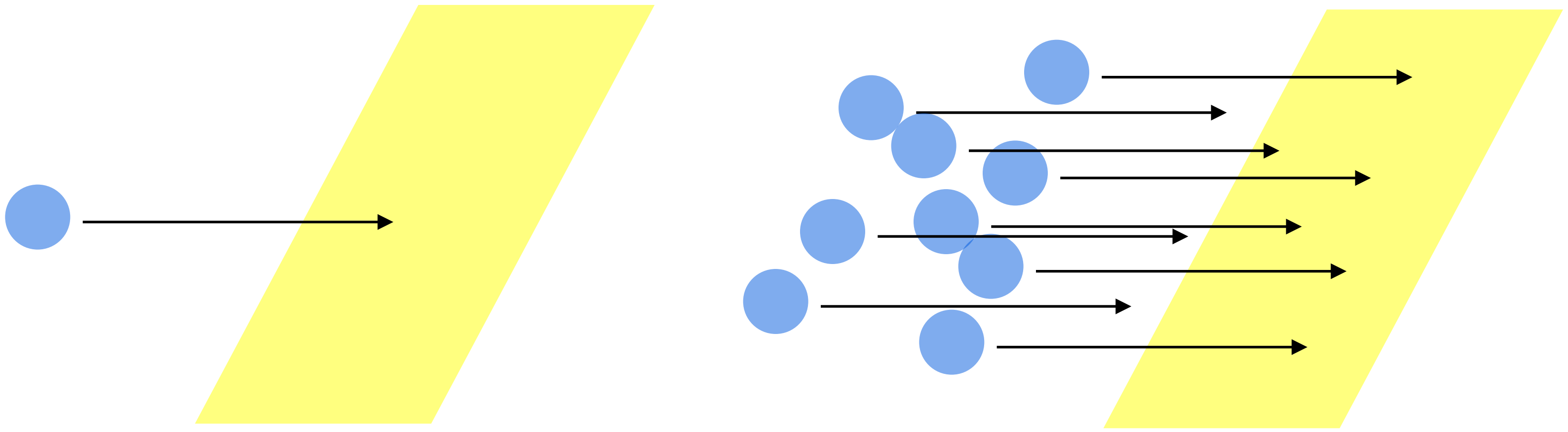
Leakage current in the insulation

- Current density
  - Comes down to the number of charges per unit time through a unit surface



  - The higher the insulation resistance, the lower the leakage current density

Leakage current in the insulation



High resistance

Low current density

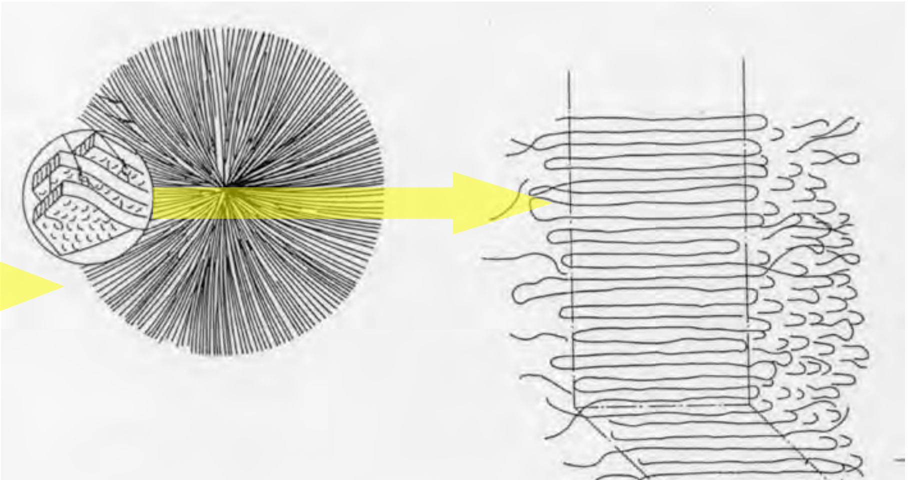
Low resistance

High current density

Leakage current in the insulation

- Smallest polymer entity in the insulation → spherulite

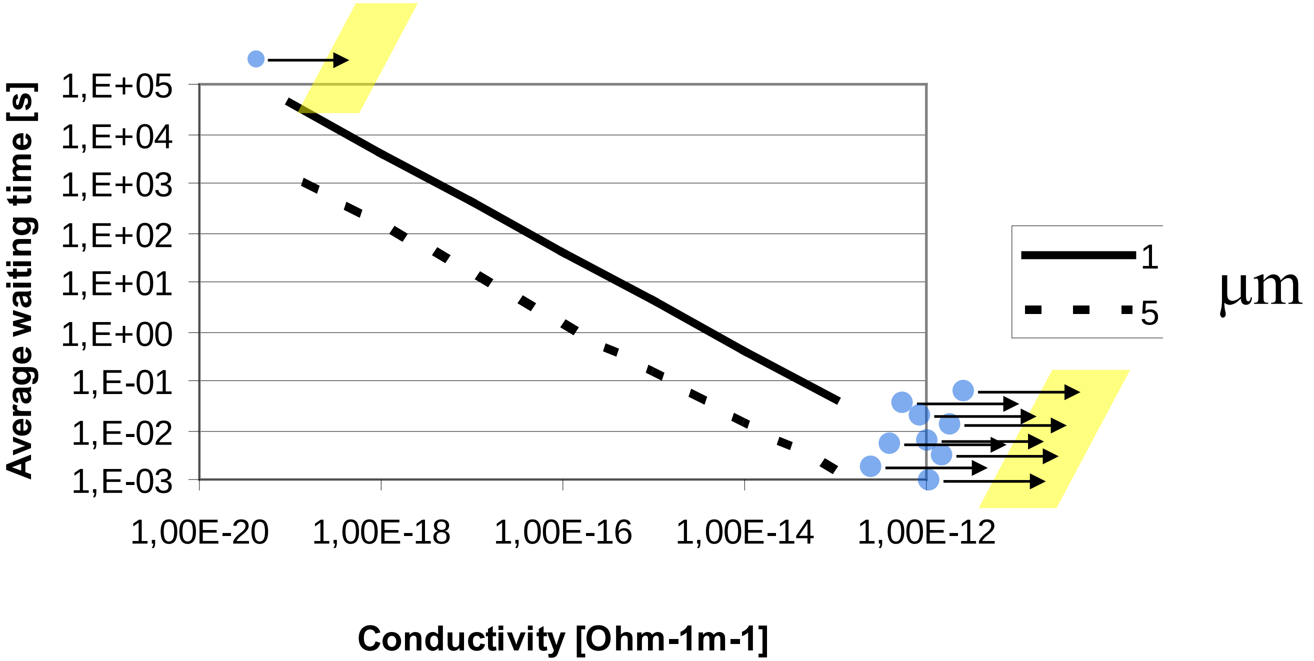
Cable insulation



Spherulite

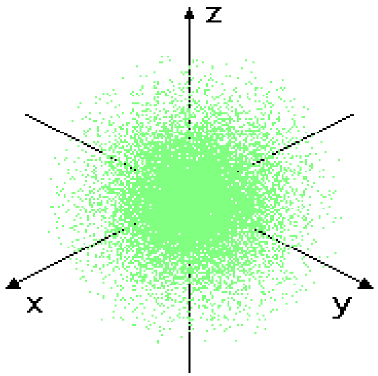
Leakage current in the insulation

- It is not so crowded with charges inside the insulation
- And on the level of a spherulite one has to wait quite some time for a charge to pass…



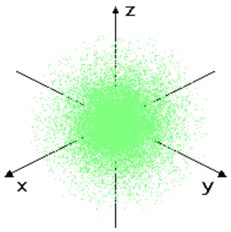
The journey

- Now we at last has arrived at the level of the charges; the electron for instance.



Now back to reality…

- Questions?



Orbital s ($\ell = 0$, $m_\ell = 0$)

Thank you for your attention!

The Principal Physics