Space Charge Measurements in Cable Insulating Materials : from Research Laboratory to Industrial Application

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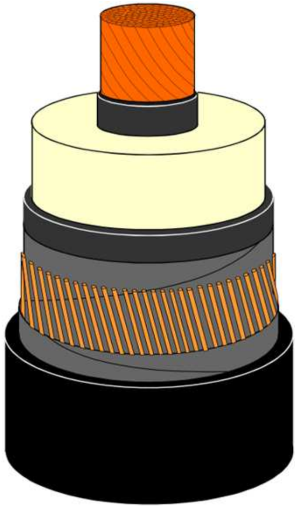
Outline of the presentation

- **Importance of measuring space Charge in HVDC insulating materials & directly in cable configuration**
- **Space Charge measurements and Thermal Step Method (TSM) applied to cable configuration**
  - Outer Cooling technique / Inner Heating technique
  - Under DC field space charge measurements
- **Application in university research laboratory**
  - Some examples
  - Recent developments
- **Application in industrial environment – Technology transfers**
- **Conclusion**

Why measuring space charge in HVDC insulating materials ?

Development of an extruded HVDC cable insulation



space charge build-up under DC field
(dangerous electric field distortions vs. time under service conditions)

Careful choice of both insulating and semi conductive materials :

- Dielectric characterisation of raw materials
- **Space charge measurements on flat samples**

Toward rules to design the system ?

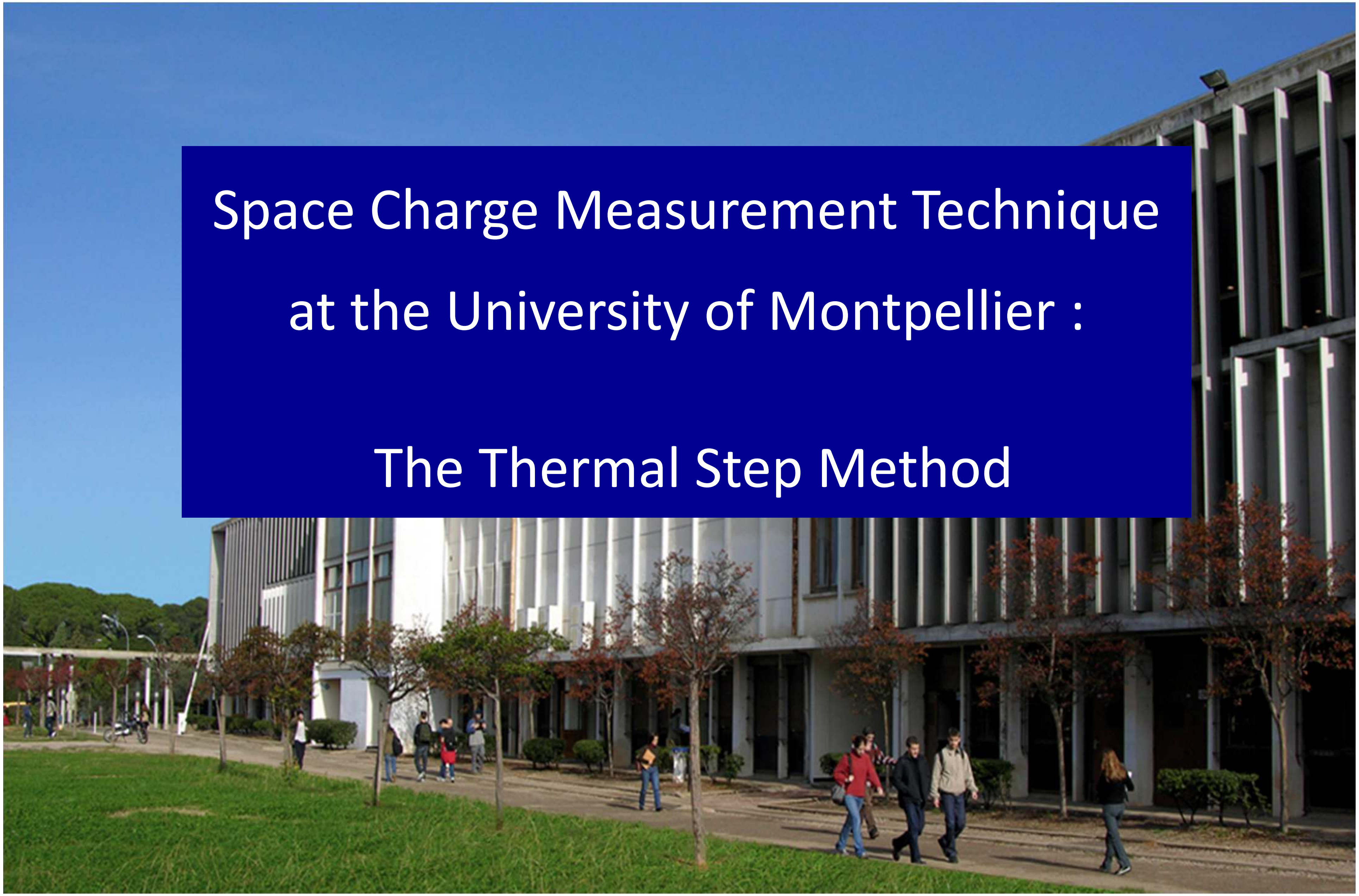
- "Resistive approach" → conduction current measurements on flat samples and theoretical calculations ?
- Long term testing, with field evolution under E,T → **comprehension of charge dynamics**

Importance of measuring space charge in cable insulation

- **Basic requirements :**
  - Insulating materials
    - High resistivity, weak temperature dependence to avoid thermal runaway
    - **Prevent space charge accumulation** (and the likely resulting brutal relaxation) : strong field dependence of resistivity to favour charge spreading out
  - Semi conductive materials
    - Limit charges injection, control of resistivity …
- **Understanding → "system" approach is needed :**
  - Insulator + semi conductive electrodes
  - **Cable configuration (importance of the manufacturing an… …on thickness)**

Space Charge Measurement Technique at the University of Montpellier :

The Thermal Step Method



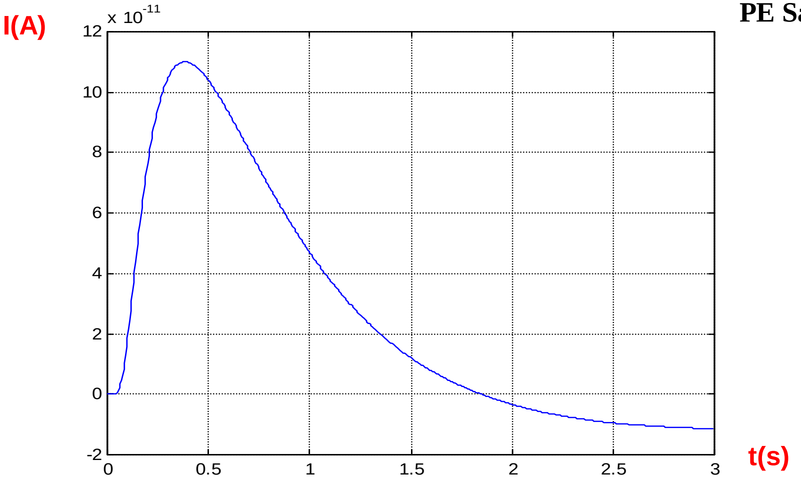
Principle of the Thermal Step Method (TSM)

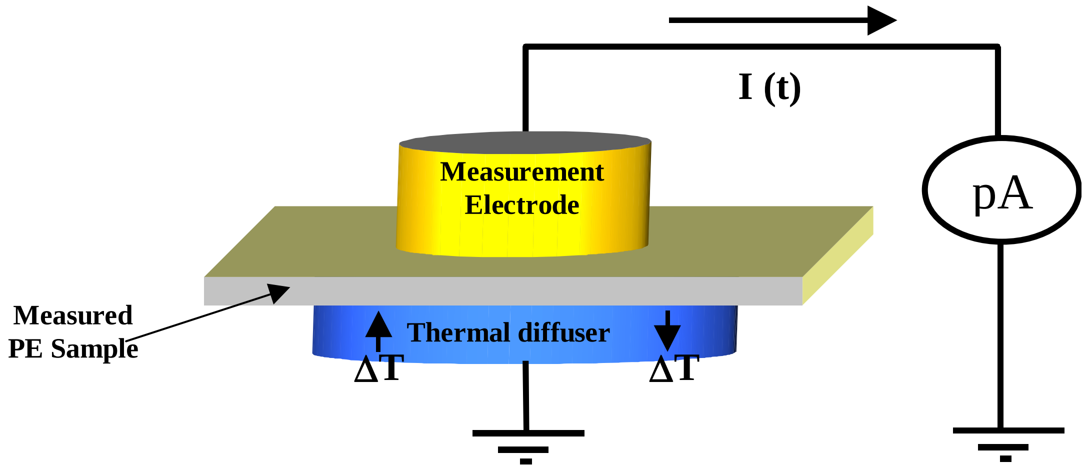
1. Short circuited sample

2. Applying the thermal step

$$dx' = dx(1+\alpha_x \cdot \Delta T)$$

$$\varepsilon' = \varepsilon(1+\alpha_\varepsilon \cdot \Delta T)$$





Balance changed → **Re-balancing**

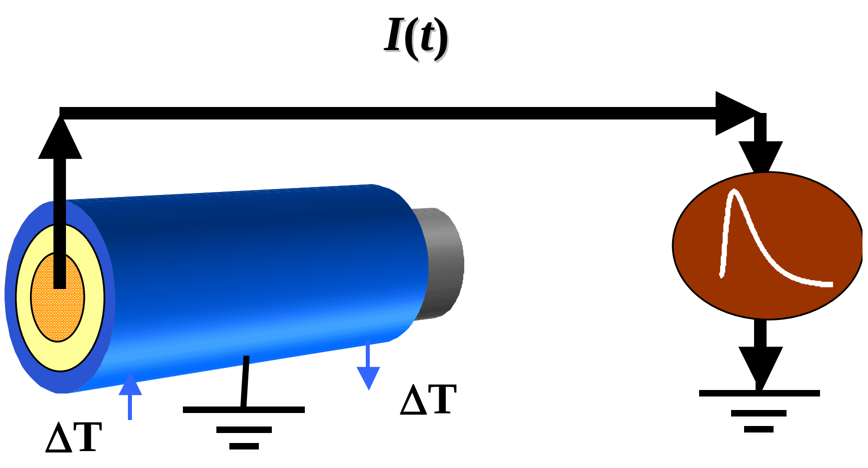
$$I(t) = -\frac{\partial Q_1}{\partial t}$$

$$I(t) = -\alpha\, C \int_0^D E(x) \frac{\partial \Delta T(x,t)}{\partial t} dx \quad \rightarrow \quad \rho(x) = \varepsilon \frac{\partial E(x)}{\partial x}$$

Non destructive technique → no modification of the electrical state

TSM applied to cable configuration : Outer Cooling Technique (OCT)

- Thermal step applied on the outer semicon layer by a heat exchanger (circular radiator enveloping the cable – 20 to 50 cm in length)
- By moving the radiator along the cable, a **cartography of the Space Charge** both in the **radius direction** and in the **length direction** can be achieved.



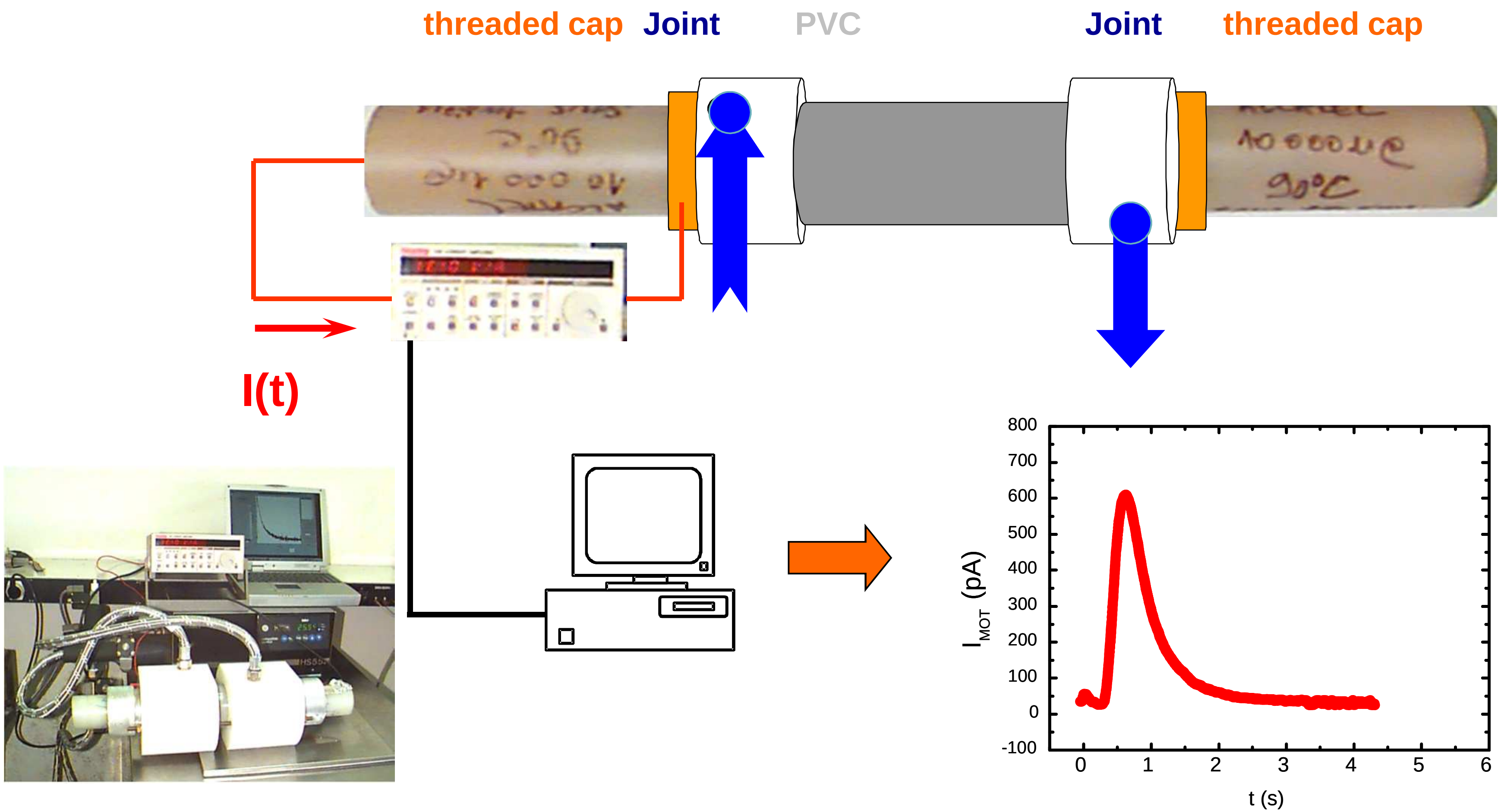
$$I(t) = -\alpha C \int_{Ri}^{Re} E(r) \frac{\partial \Delta T(r,t)}{\partial t} dr$$

➡ TSM gives the RADIAL distribution of the charge ρ **(r)**

$$\rho(r) = \varepsilon\left(\frac{E(r)}{r} + \frac{\partial E(r)}{\partial r}\right)$$

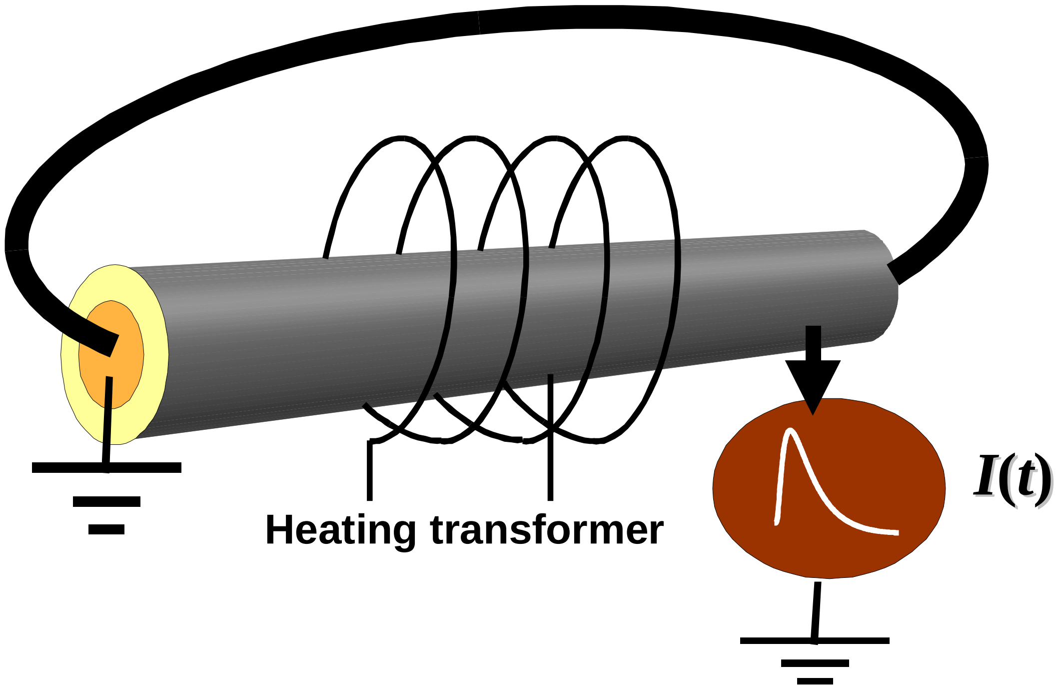
TSM applied to cable configuration : Outer Cooling Technique (OCT)

Experimental set-up : Measurements in short-circuit conditions



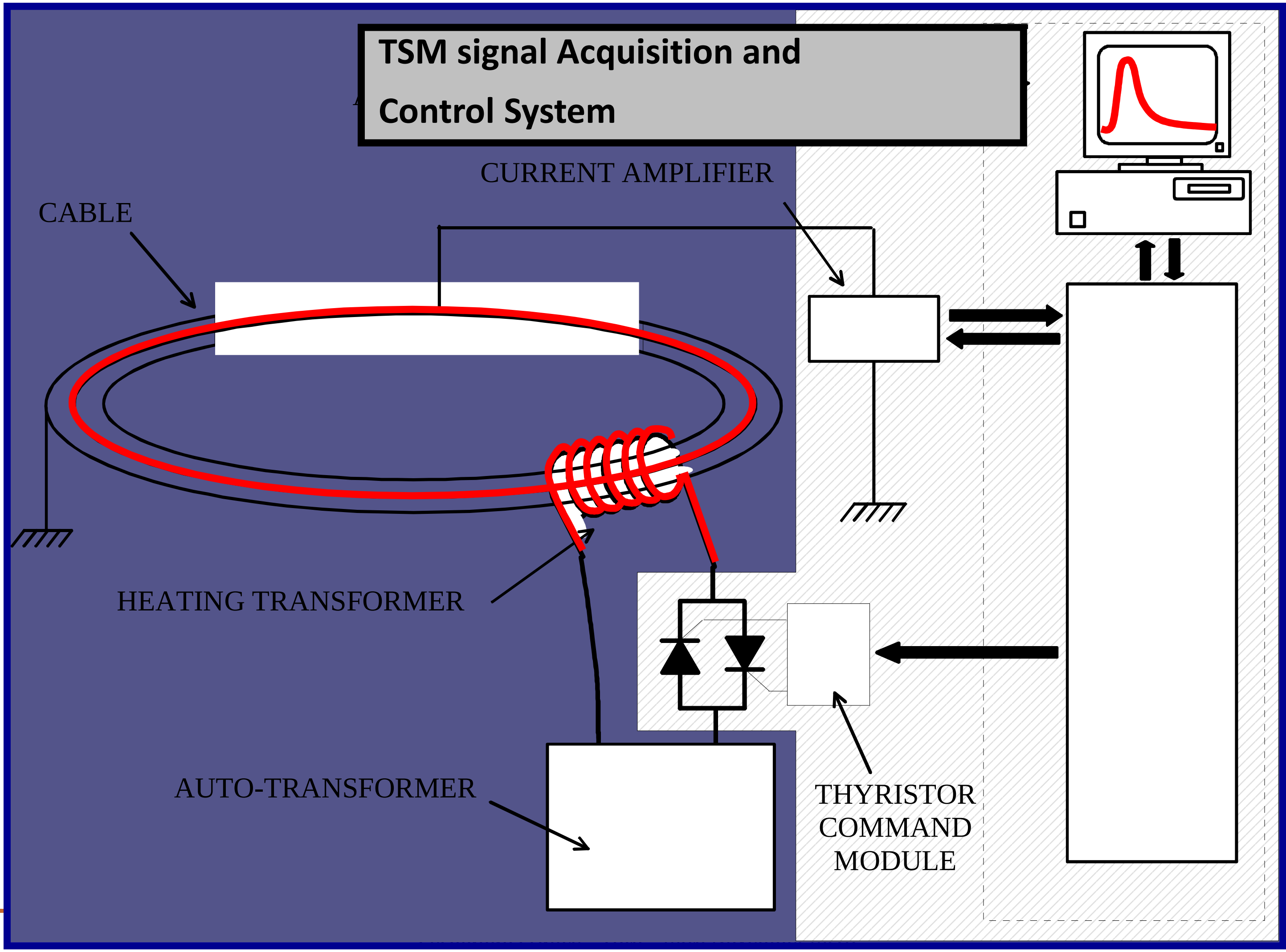
TSM applied to cable configuration : Inner Heating Technique (IHT)

- Joule effect induced by a strong current (several kA) circulating through the cable core to generate the thermal wave.
- Gives a **global evaluation** of the charging state **of the entire cable insulation** (cable length)



TSM applied to cable configuration : Inner Heating Technique (IHT)

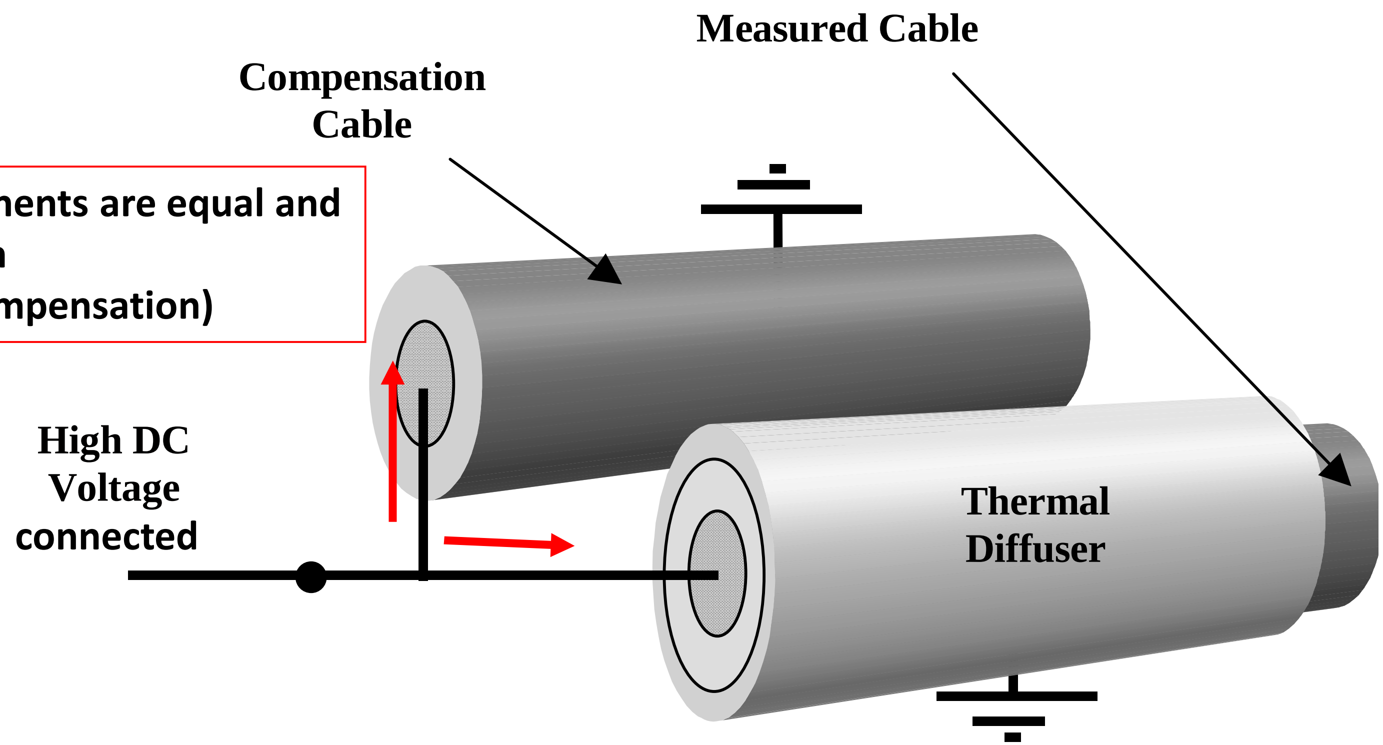
Experimental set-up : Measurements in short-circuit conditions



TSM under DC applied field : The "double capacitor"

Under Field measurements → « Double Capacitor » Technique

Current components are equal and of opposite sign (principle of compensation)



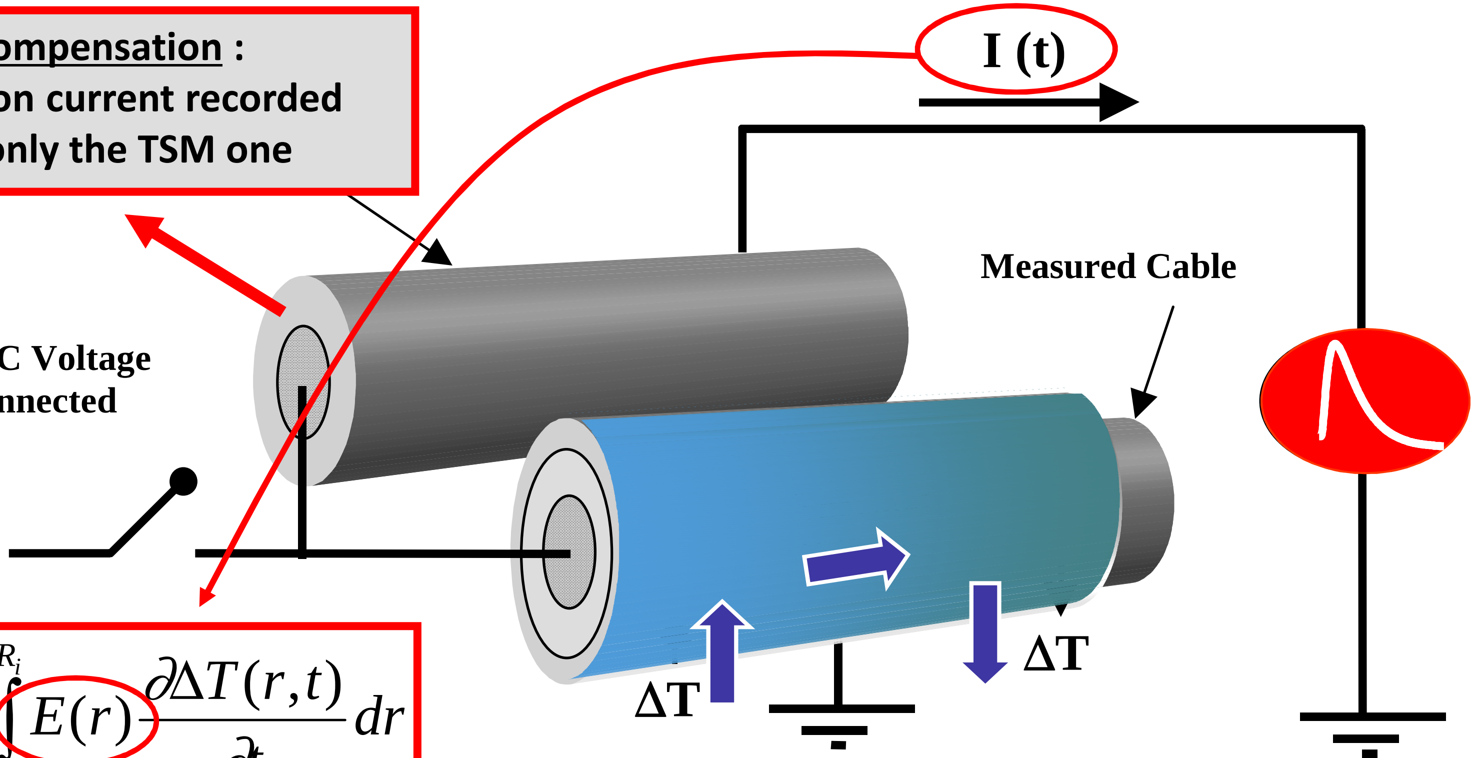
Two cables with the same C

1: Poling stage

TSM under DC applied field : The "double capacitor"

Under Field measurements → « Double Capacitor » Technique

Owing to the compensation :
None conduction current recorded by the pA but only the TSM one



$$I(t) = -\alpha C_2 \int_{R_e}^{R_i} E(r) \frac{\partial \Delta T(r,t)}{\partial t} dr$$

$C_2 = C/2$

2 : HV disconnected, measurement launched

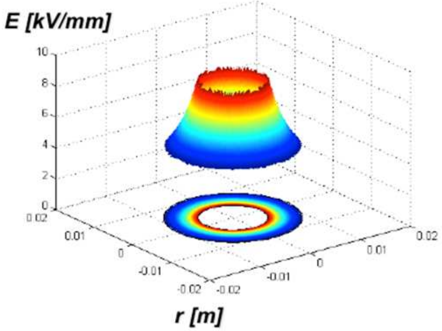
TSM under DC applied field : Calibration

Considering "unaged" cables (very low space charge level)

For a low applied voltage V

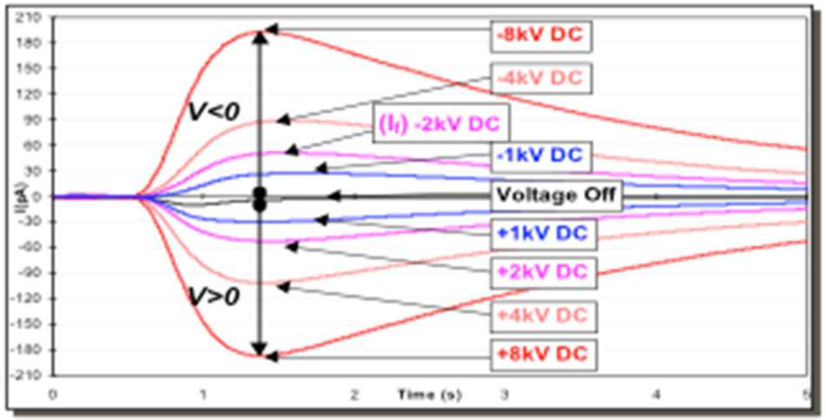
$$E(r) = \frac{V}{r \ln \frac{R_e}{R_i}}$$

(Laplace Field)



$$I(t) = -\alpha C_2 \frac{V}{\ln \frac{R_e}{R_i}} \int_{R_e}^{R_i} \frac{1}{r} \frac{\partial \Delta T(r,t)}{\partial t} dr$$

TSM current directly proportional to applied voltage



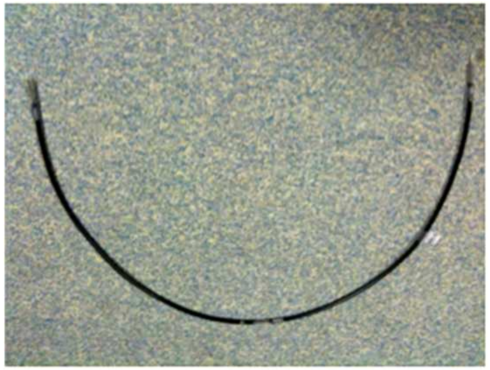
Calibration

Application of the technique in research laboratory :

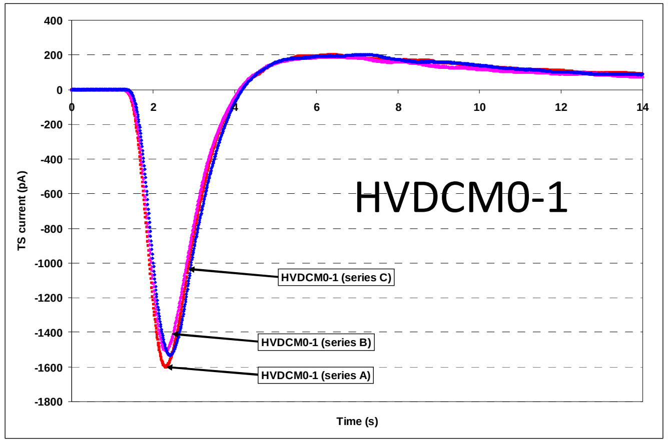
some examples of research experiment

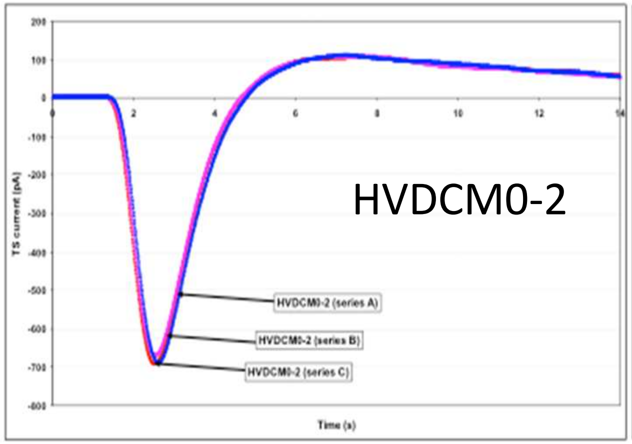
By using the Outer Cooling Technique (OCT)

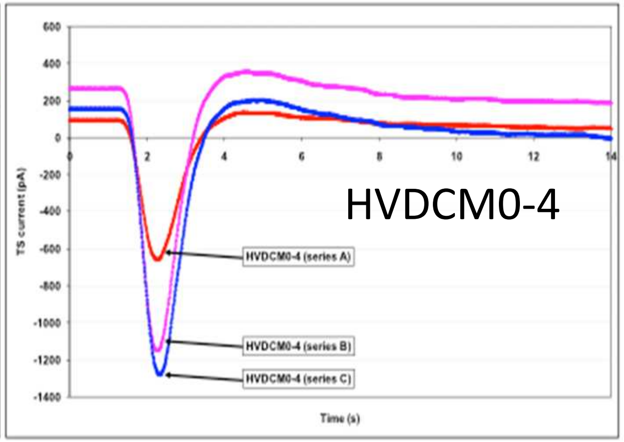
Evaluation of **insulating systems for HVDC cable design** toward **Space Charge criterion**



- **3 miniature cables** (model cables) with 3 different couples "insulating material / semicon" : HVDCM0-1, M0-2, M0-4
- Insulation **thickness** : 2,6 mm
- Each "cable" length cut in **3 samples** to test the longitudinal homogeneity



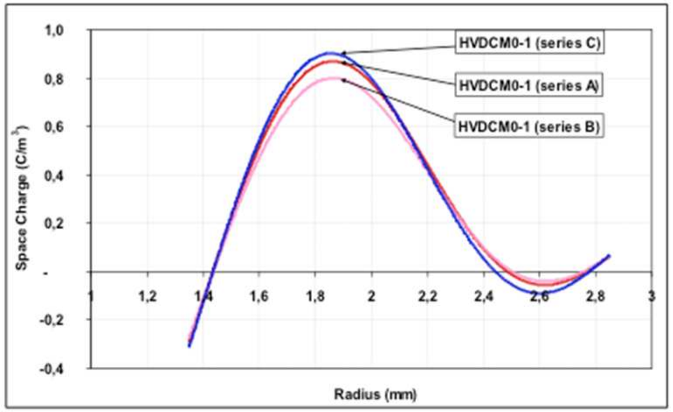


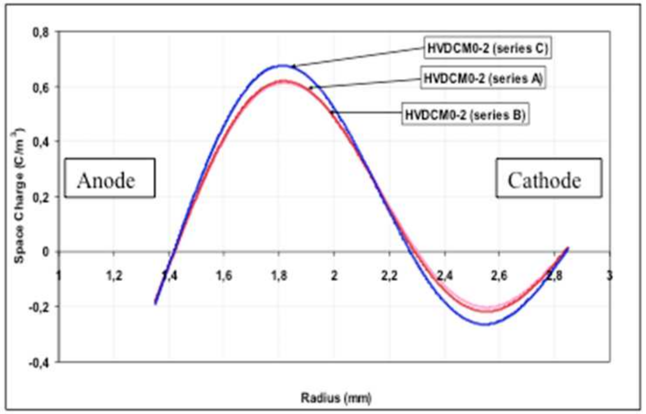


TSM currents after 20 kV dc, 70° C, 4 h

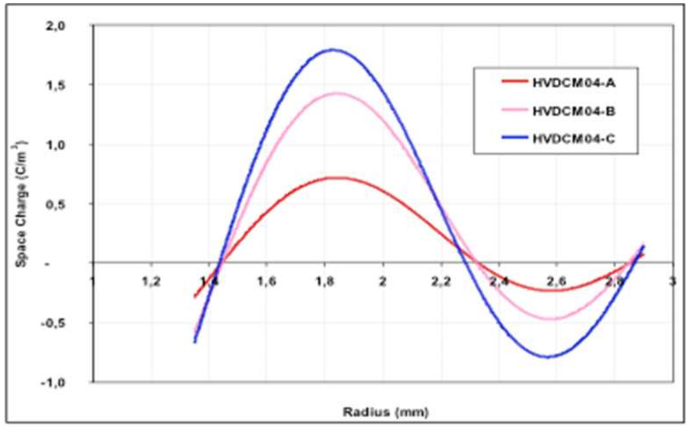
By using the OCT : Evaluation of insulating systems for HVDC cable design toward SC criterion (2)

- The SC distributions confirm a **good longitudinal homogeneity** of the cables HVDCM0-1 and 2 (”very” similar distributions)
- Difference in SC amplitudes for cables HVDCM0-1 and HVDCM0-2 (≅ factor 2 – less space charges in cable HVDCM0-2)





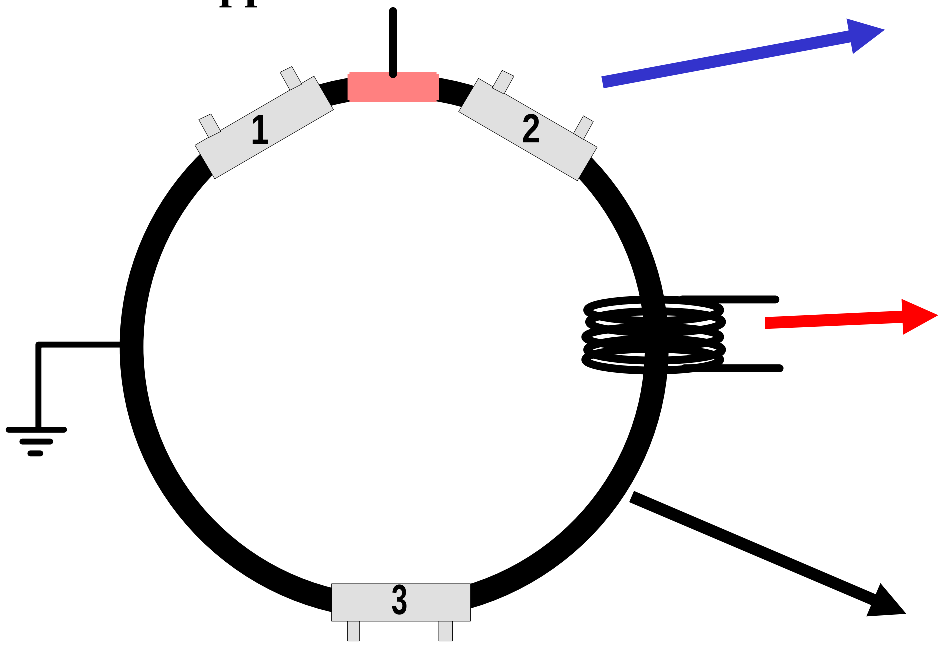
- Cable HVDCM0-4 highlights a longitudinal heterogeneity



Complementary use of OCT and IHT – measurements in power cable length

To show the possibility to evaluate, **locally** and **globally**, the **electrical state** of a **significant cable length**

3 m long cable coming from a **commercially available 12/20 kV cable** (aluminium core of 95 mm^2)



3 thermal diffusers to observe the homogeneity of the dielectric behavior of the insulator (OCT)

AC Heating transformer :
- to generate the heating current for IHT
- to establish a current close to the nominal value (~200A) during the electrical conditioning (40 kV dc - thermal gradient 40° C – 12 h)

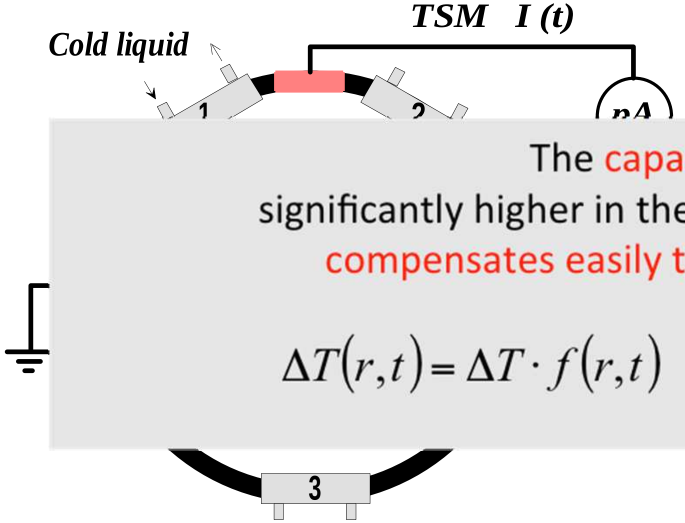
The ends are connected to constitute a single-turn secondary of the heating transformer

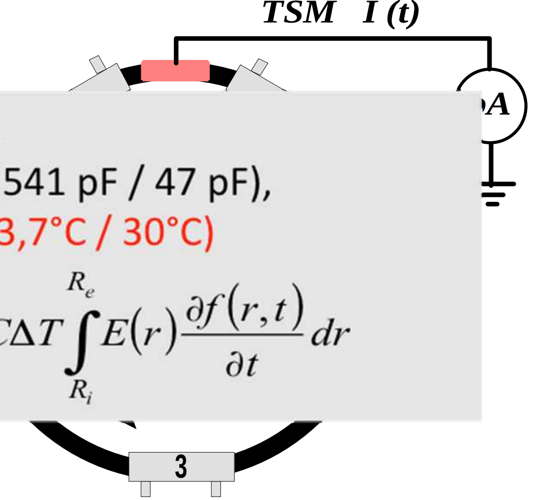
Complementary use of OCT and IHT – measurements in power cable length

Thermal step : -30° C

I = 2475 A rms (AC heating current)

0.05s to 0.5s → 0.36 to 3.7° C

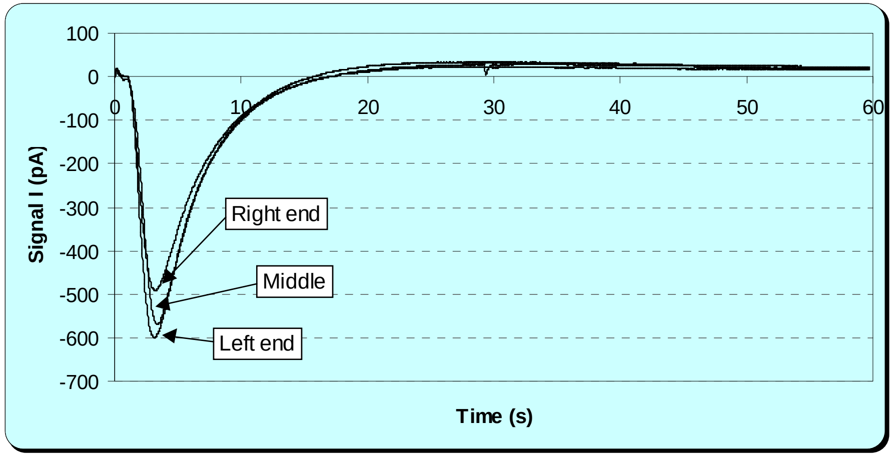


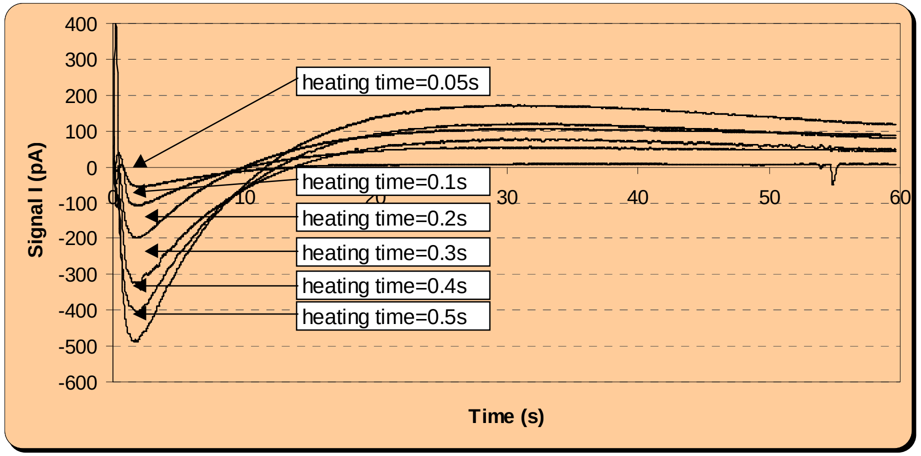


The capacitance of the cable length,
significantly higher in the case of the inner heating (541 pF / 47 pF),
compensates easily the low temperature raise (3,7°C / 30°C)

$$\Delta T(r,t) = \Delta T \cdot f(r,t)$$

$$I(t) = -\alpha C \Delta T \int_{R_i}^{R_e} E(r) \frac{\partial f(r,t)}{\partial t} dr$$





Close and Return

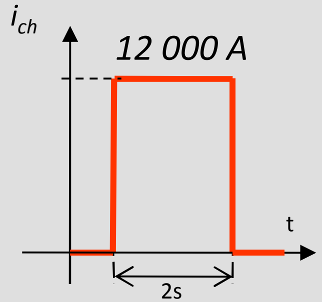
Recent developments : Portable installation for SC measurement on full-size HVDC cable

Develop
High Vol

Following
dynamics
loops du
testing

TARGET : measurement on a 500 kV HVDC cable loop

- length : 100 m
- conductor section : 2500 mm²
- portable system
- system usable on-site during type tests



➔ current pulse of 12000 A during 2 s for a ΔT = 0.5 K

➔ ability to measure transient current responses ~ 1 pA

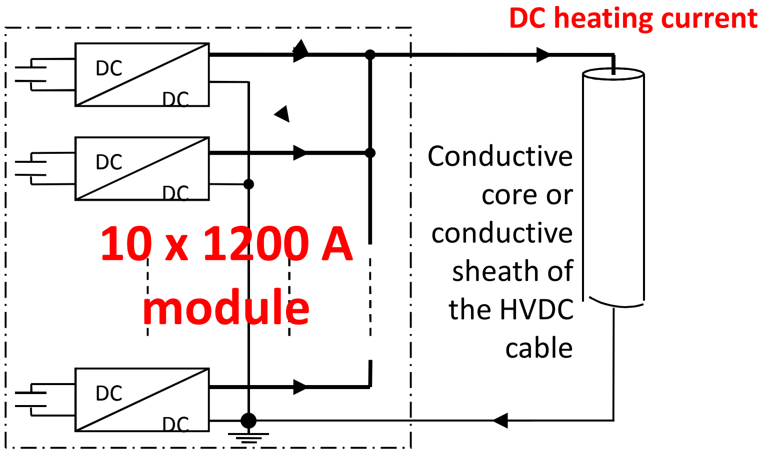
bal
aluation

- Heating transfo… er (AC, 50 Hz)
  - cable core = ind… ce ➔ app… power ~ 1 MVA !
  - partial control of the … urrent waveform
  - volume >>
  - €€€ …

* J. Matallana, T. Kvarts, B. Sanden et al., "Recommendations for testing DC extruded cable systems for power transmission at a rated voltage up to 500 kV", CIGRE Work Group B1.32, Technical Brochure 496, 2012

Recent developments : Portable installation for SC measurement on full-size HVDC cable

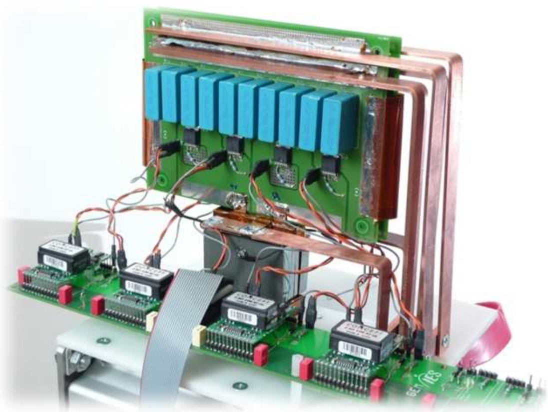
Solution : Low voltage, High current **DC/DC converter**
+ low current measurement system



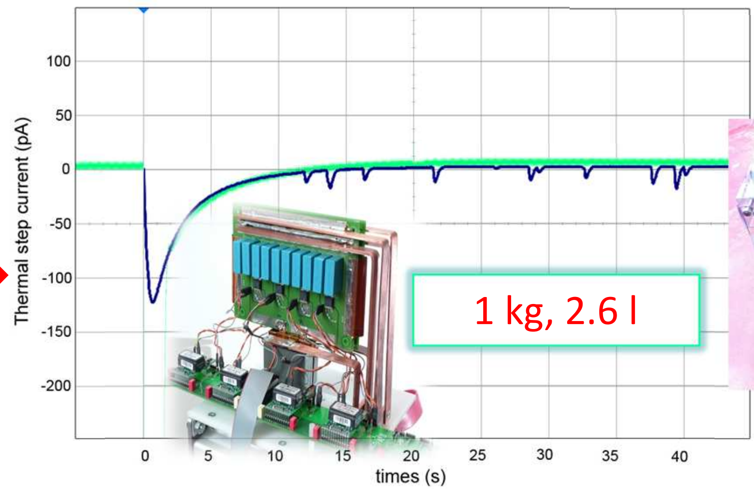
12 000 A DC/DC converter

Prototype :

1200 A module
2 kg, 5 l



Prototype tested and validated to be used with the principle of the TSM (Inner or Outer Heating)

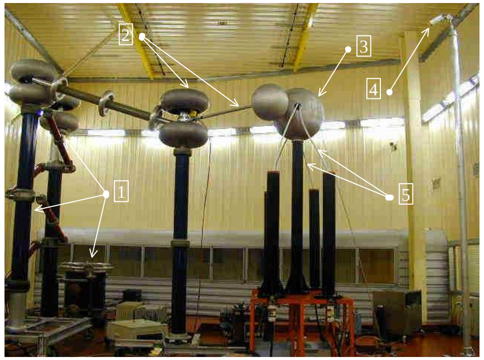


AC heating transformer

70 kg, 30 l

Application of the TSM in industrial environment

Technology transfers



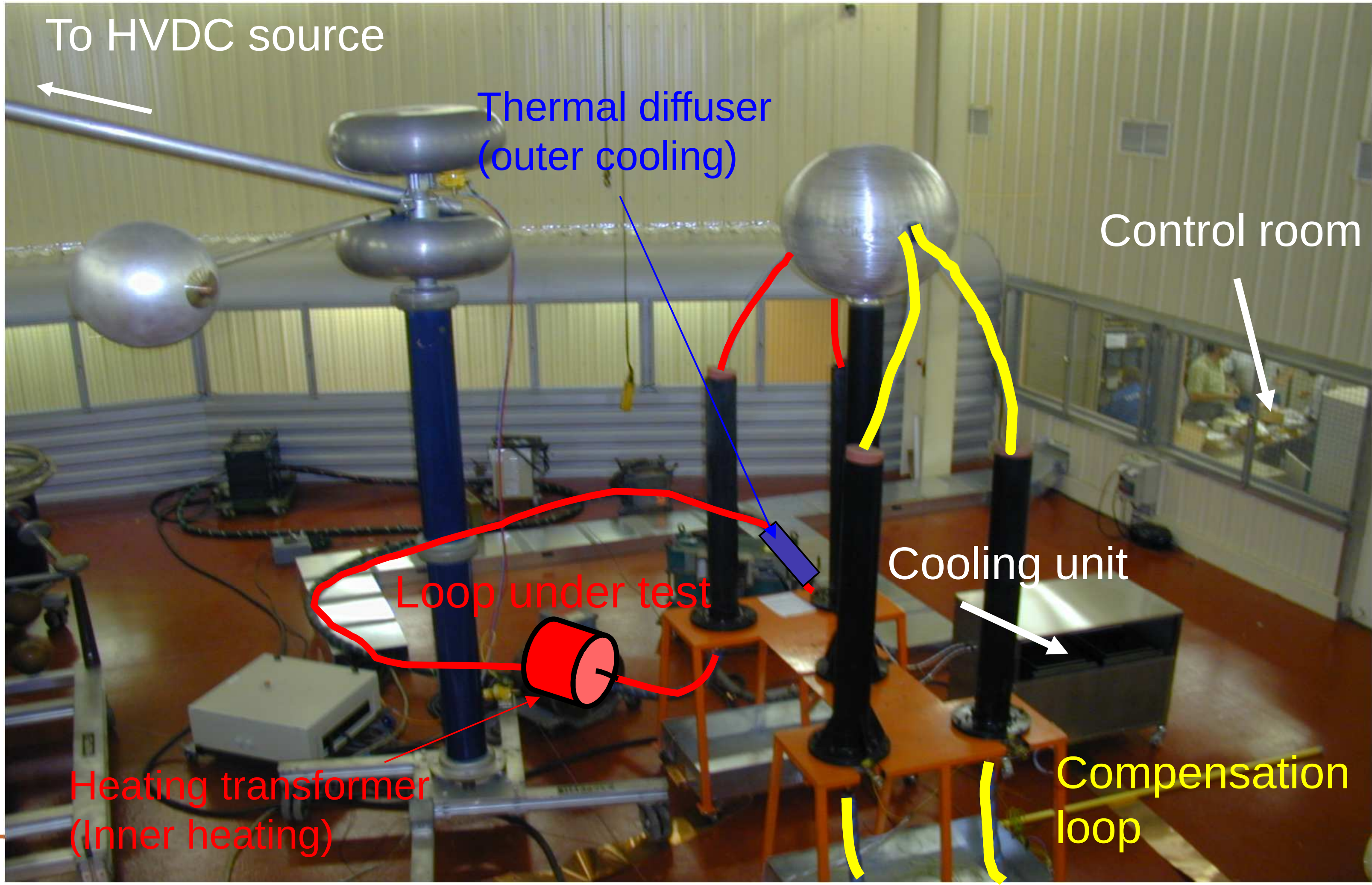
2001
NEXANS (Calais – F)
HVDC cable (model cables)

2006
LABORELEC – Suez (Linkebeek - B)
AC cable (lengths of 0,3 m)

Industrial TSM facilities available in NEXANS Competence Center (Calais)

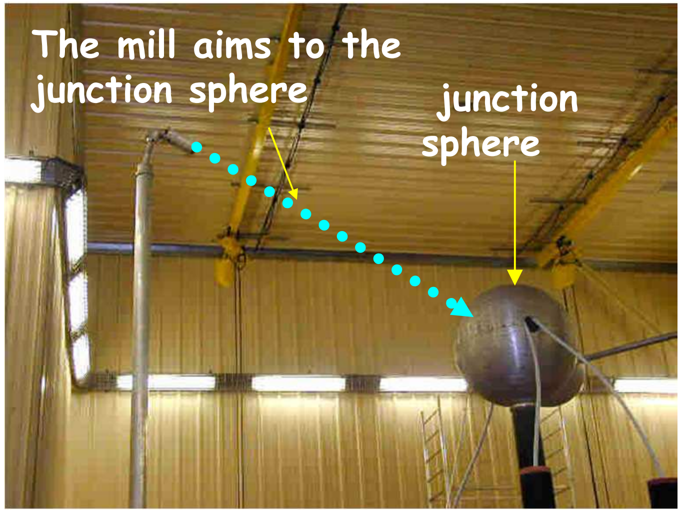
Set-up gathering all features described previously :

- Measurements in **short circuit conditions** (residual steady space charge build-up)
- Measurements **under applied field and ΔT →** evolution of field distortions under service conditions

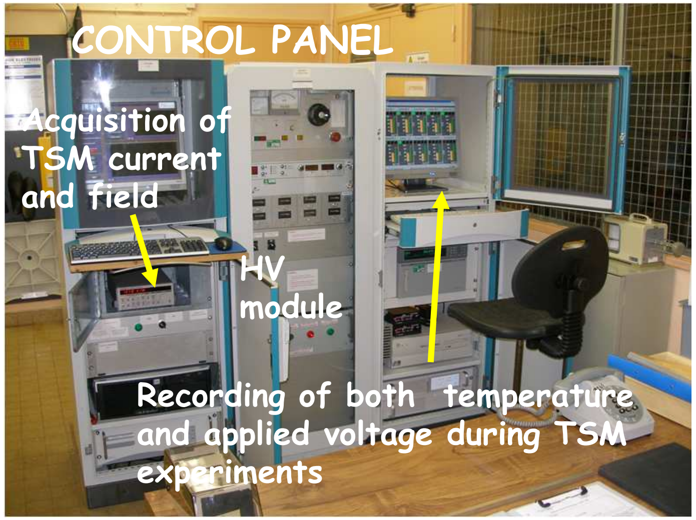


Industrial TSM bench : specificities

Continuous recording of applied voltage (field mill)



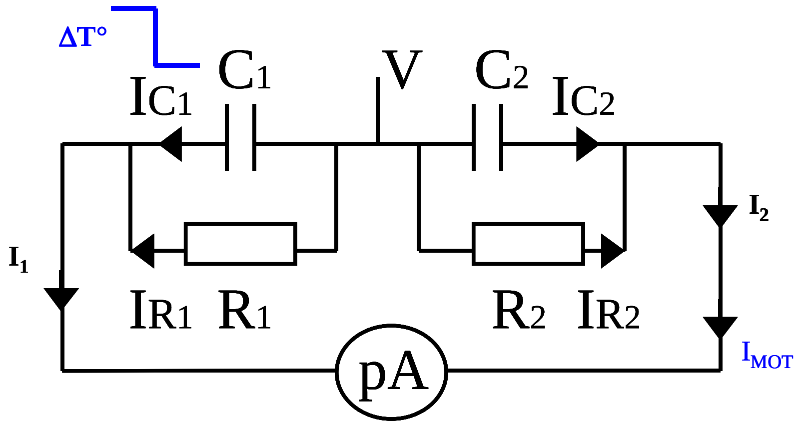
TSM Measurements under continuous heating



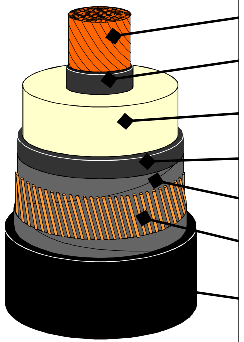
If "Differential current" between the 2 cables under test is too strong (super-imposed to the TSM current) :

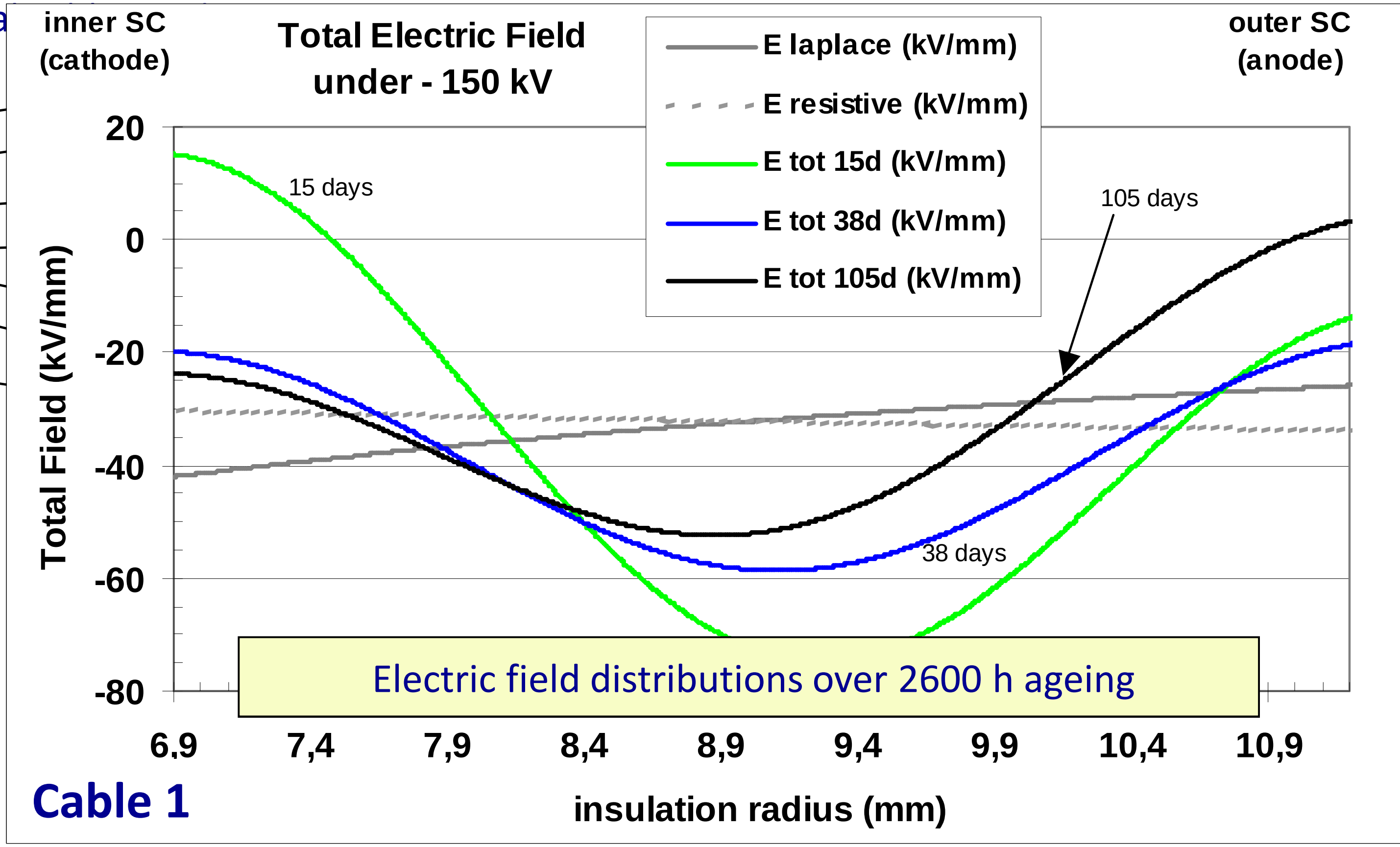
- Due to thermal gradient and/or an eventual potential decay during measurement

→ voltage-off (short circuit) measurements are preferred as an alternative solution



Monitoring of the electric field under applied field and thermal gradient (voltage-on)

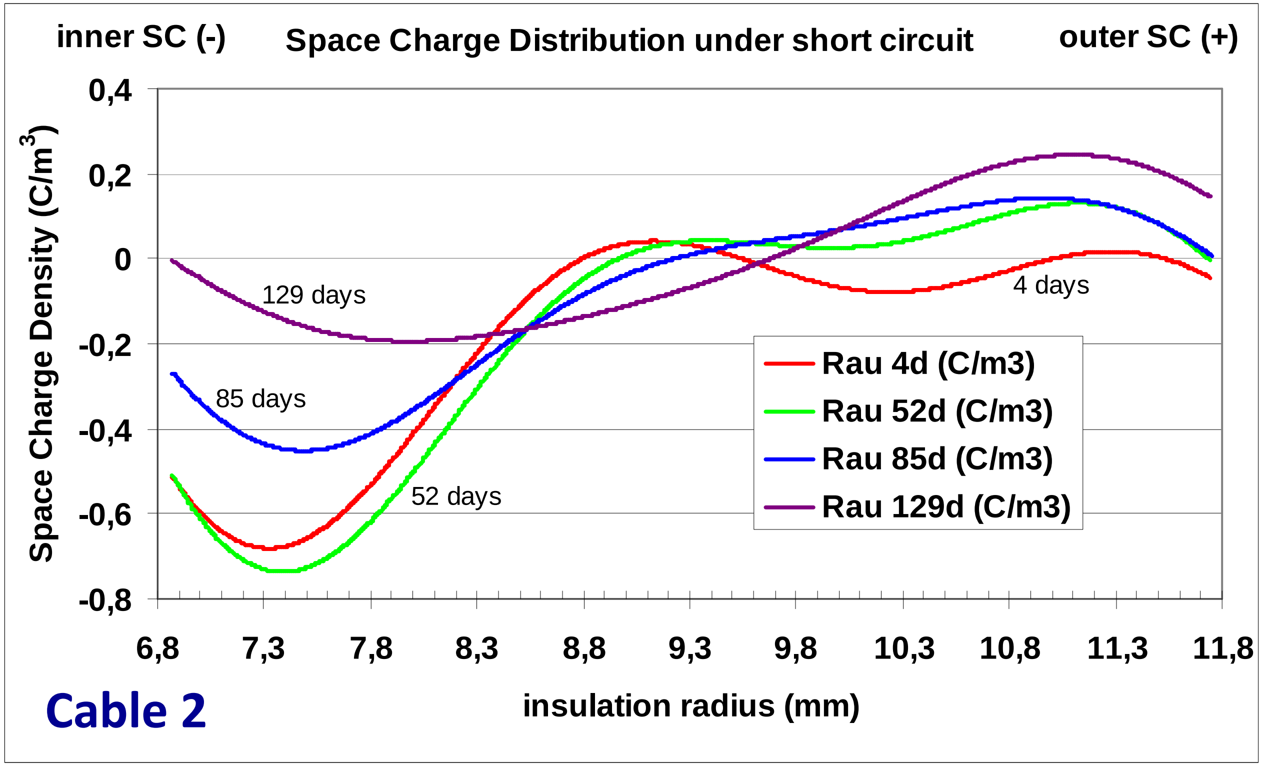




- Smoothening of field distribution as a function of ageing duration.
- Tendency observed toward a “resistive” behaviour (hidden by charge injection at anode / more visible at cathode where injection vanishes).

Monitoring of the residual space charge during ageing (voltage-off)

- Space charge measurements – ageing under – 230 kV (63 kV/mm applied) over 3400 h
- Voltage-off measurements (short-circuit) due to potential decay and differential currents



- Significant evolution of each type of carriers (relatively limited charge levels 0.2-0.8 C/m^3):
  - building-up of positive charges at the anode (and motion toward the bulk)
  - negative charge at the cathode decreases and is spread out in the bulk of insulation.

Conclusion

- **TSM has been invented in 1986 in university research laboratory** for measuring space charge in solid insulating materials
- **Non destructive characterization technique** allowing to study the charge accumulation phenomena in materials, but also in **components for electrical engineering (cables)**
- For extruded **cables** :
  - Two variants (OCT - Cartography of space charge / IHT for a Global evaluation of the insulation)
  - "Short circuit" (Voltage-off) or "Under field" (Voltage-on) measurements
- **Technique transferred in industry** (for measuring space charge and electric field in cable insulation in industrial environment)

In progress …

ALSTOM Grid UK, NEXANS France, VISCAS Japan, Montpellier & Leicester University

develop a **world 1rst ever HVDC cable long term ageing evaluation facility,**

combining **online measurement methods (TSM, PEA …)**

on full-size 200 kV cables undergoing a program of ageing similar to the

CIGRẾ prequalification test.

ALSTOM | Grid

Nexans

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Thank you
for your attention

Any questions