



Estudio de las propiedades fractales de árboles eléctricos y de la dinámica de las descargas parciales involucradas en la degradación de aislamientos eléctricos

Roger Schurch

Departamento de Ingeniería Eléctrica

Presentación (adaptada) para asignatura Laboratorio de Modelación MAT-288
4 de abril de 2016

TEMA 1

Propiedades fractales de árboles eléctricos



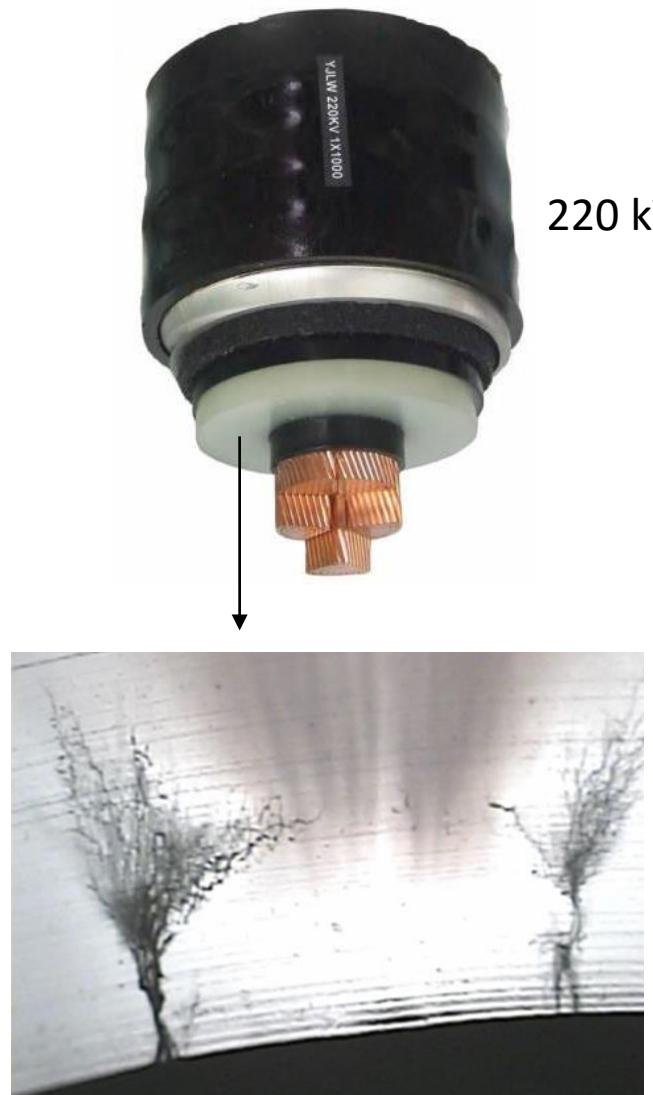
Overview

1. Background
2. Experimental description
3. Examples of 3D geometrical models
4. Fractal dimension

- 1. Background**
2. Experimental description
3. Examples of 3D geometrical models
4. Fractal dimension

Electrical Trees

- Tubular channels of degradation in HV polymeric insulation.
- Precursor to failure of electrical power equipment: bushings, cables, electrical machines and switchgear.
- Initiation and growth mechanisms are not fully understood.



Crecimiento del árbol y falla



The University of Manchester

Electrical breakdown through an electrical tree

R. Schurch, S. M. Rowland, R. S. Bradley and J. P. Withers
"A Novel Approach for Imaging of Electrical Trees"
IEEE Conference on Electrical Insulation and Dielectric Phenomena, Montreal - 2012

R. Schurch, S. M. Rowland and J. P. Withers
"Techniques for Electrical Tree Imaging"
IEEE Conference on Imaging Systems and Techniques, Manchester - 2012

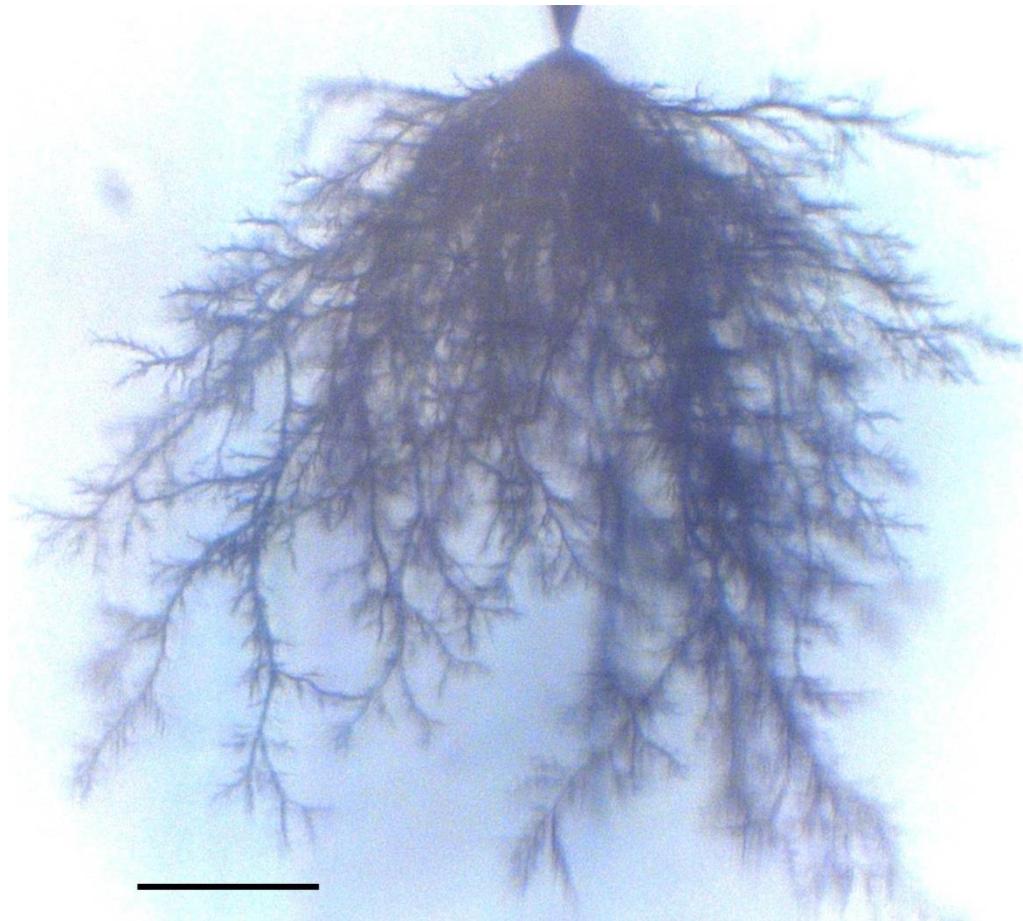
<http://www.youtube.com/user/ElectricalTreesCEIDP/videos>

Types of trees

Branch-type



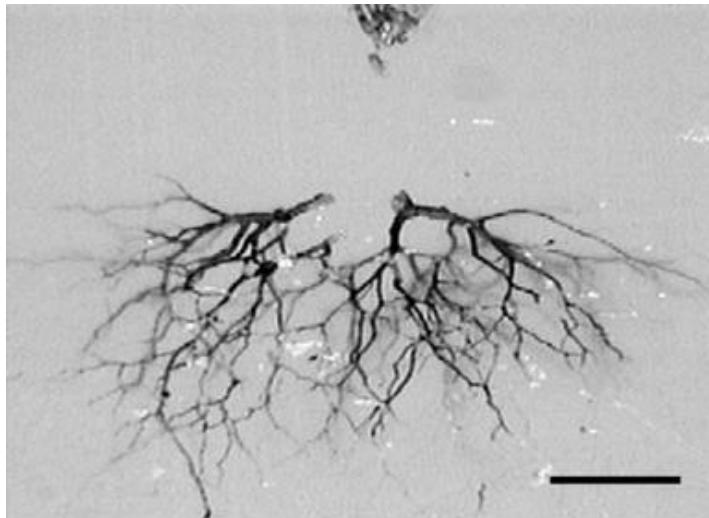
Bush-type



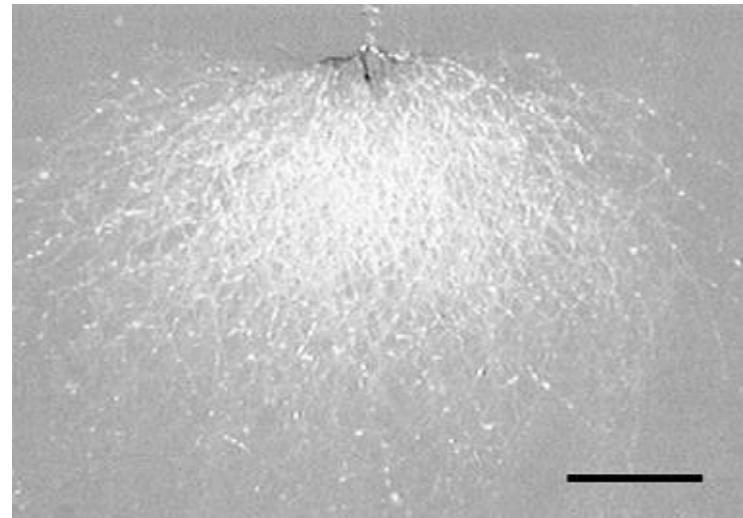
Scale bars: 200 µm

Types of trees (2)

Conducting structure



Non-conducting structure



Scale bars: 200 µm

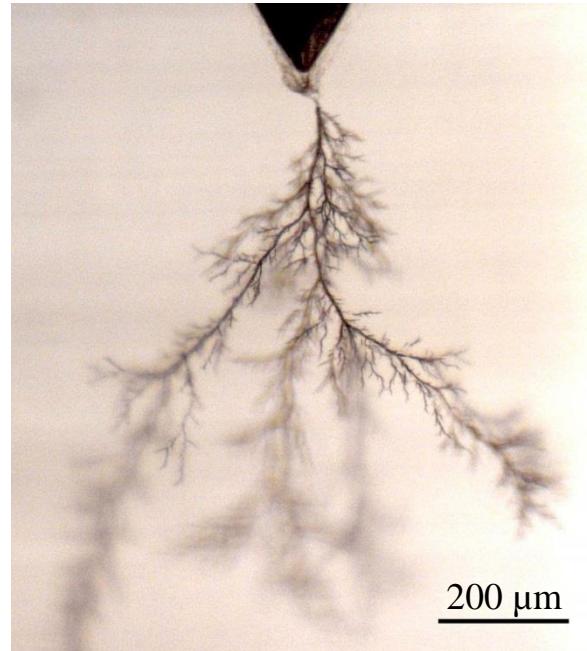
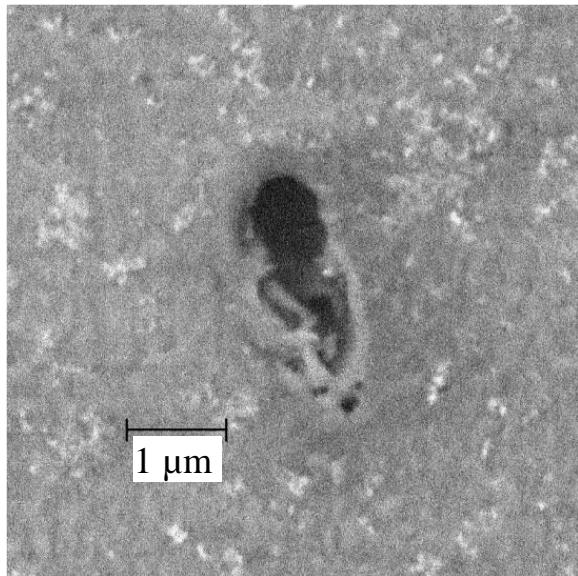
A. S. Vaughan, S. J. Dodd, and S. J. Sutton,
Journal Materials Science, Vol. 39, pp. 181-191, 2004.

Importance of studying Electrical Trees

- Study the mechanisms involved in the phenomena
- Lead to improved insulation design and asset management
 - increase reliability of power networks
 - achieve challenges of new requirements of plant compaction and energy loss reduction

Traditional imaging approach: 2-D

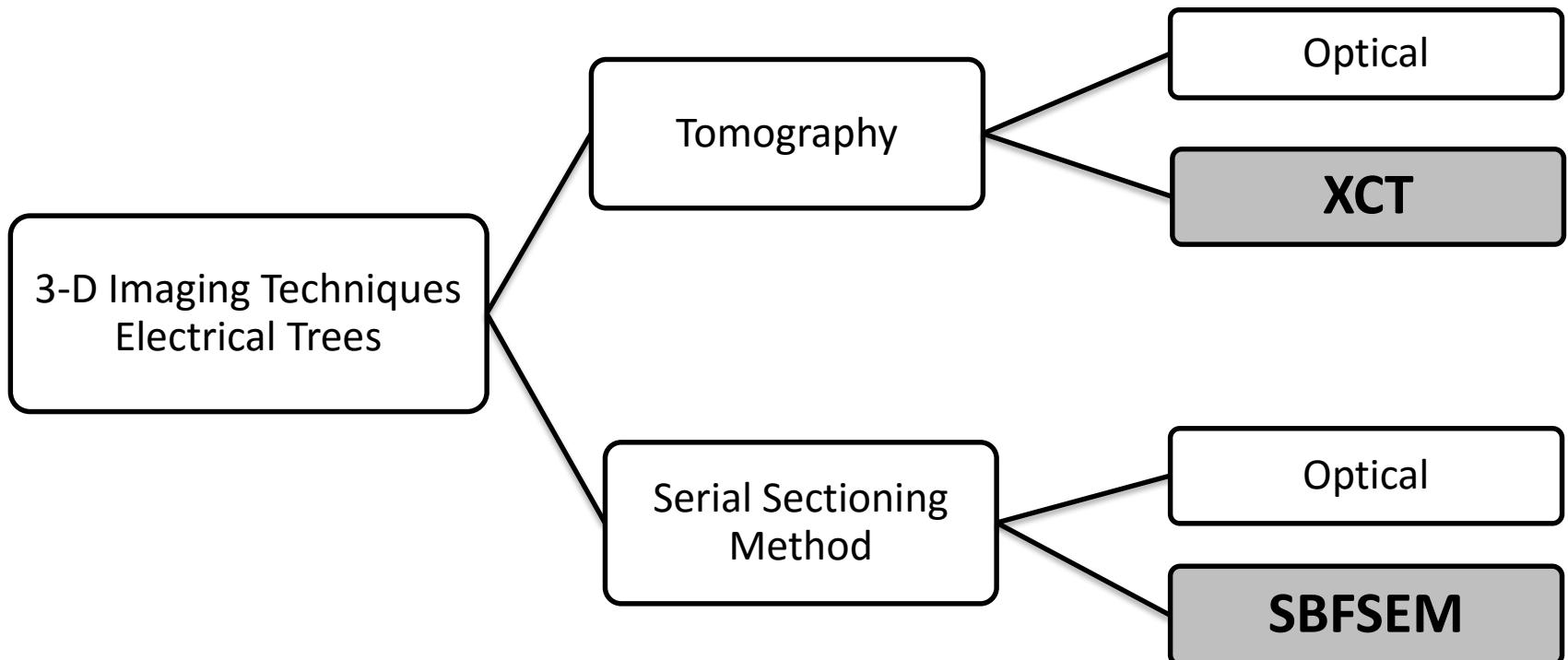
- Optical microscopy



- Scanning Electron Microscopy (SEM)

3-D Approaches for Electrical Trees

- Complex interconnected structures require 3D approaches



1. Background
2. **Experimental description**
3. Examples of 3D geometrical models
4. Fractal dimension

Methodology

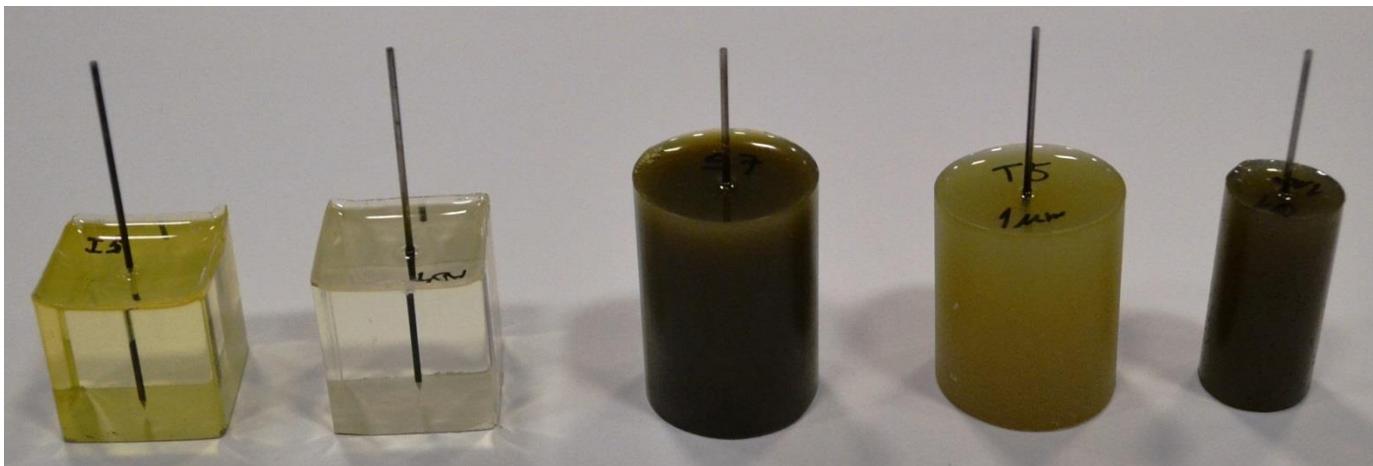


Procedure of imaging and analysis of electrical trees

Experimental Procedure (1)



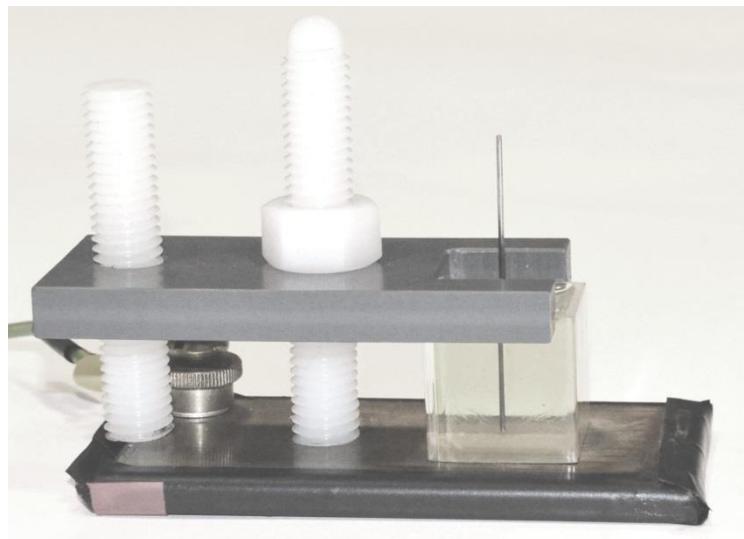
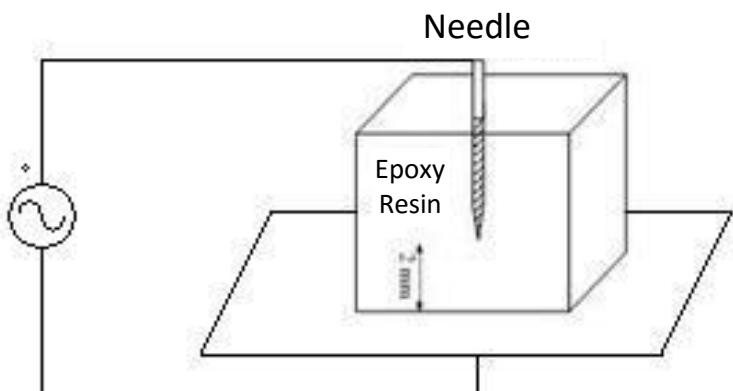
- Material: epoxy resin
- Conventional point-to-plane configuration



Experimental Procedure (2)



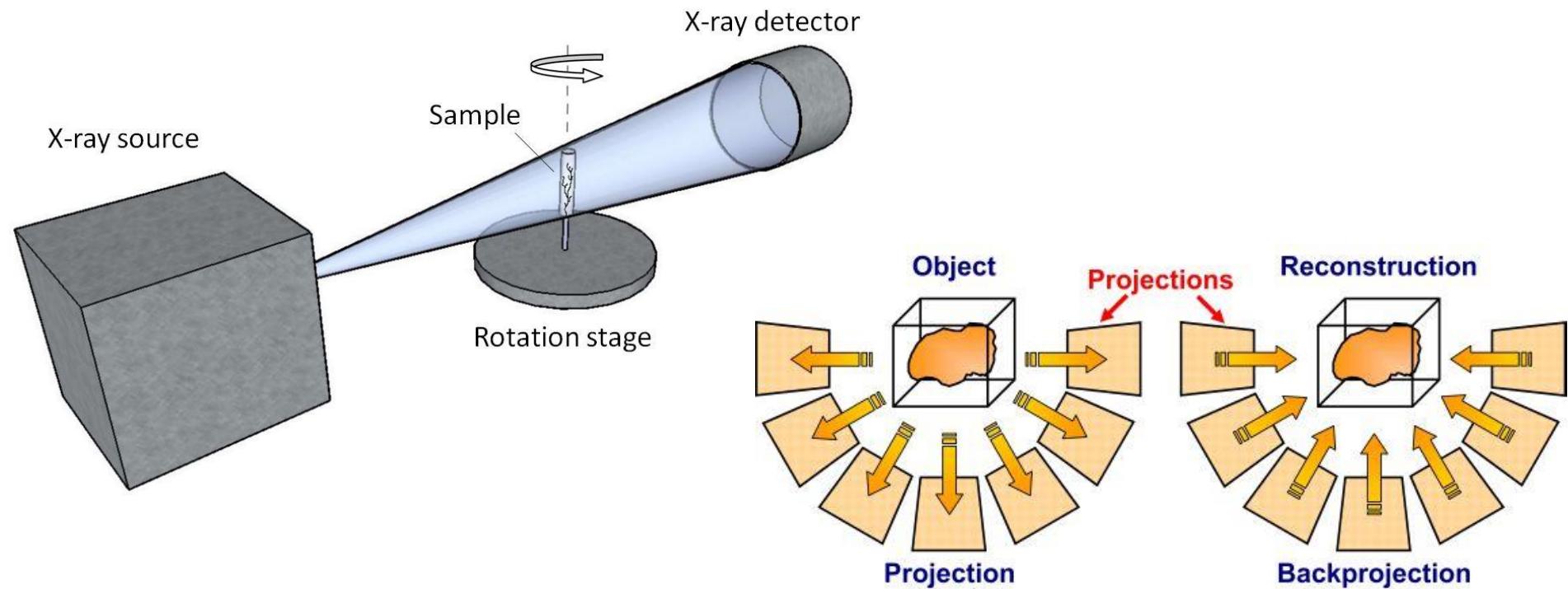
- Tree growth: High voltage (~ 10 kVrms) AC 50 Hz



Experimental Procedure (3a)



X-ray Computed Tomography (XCT)

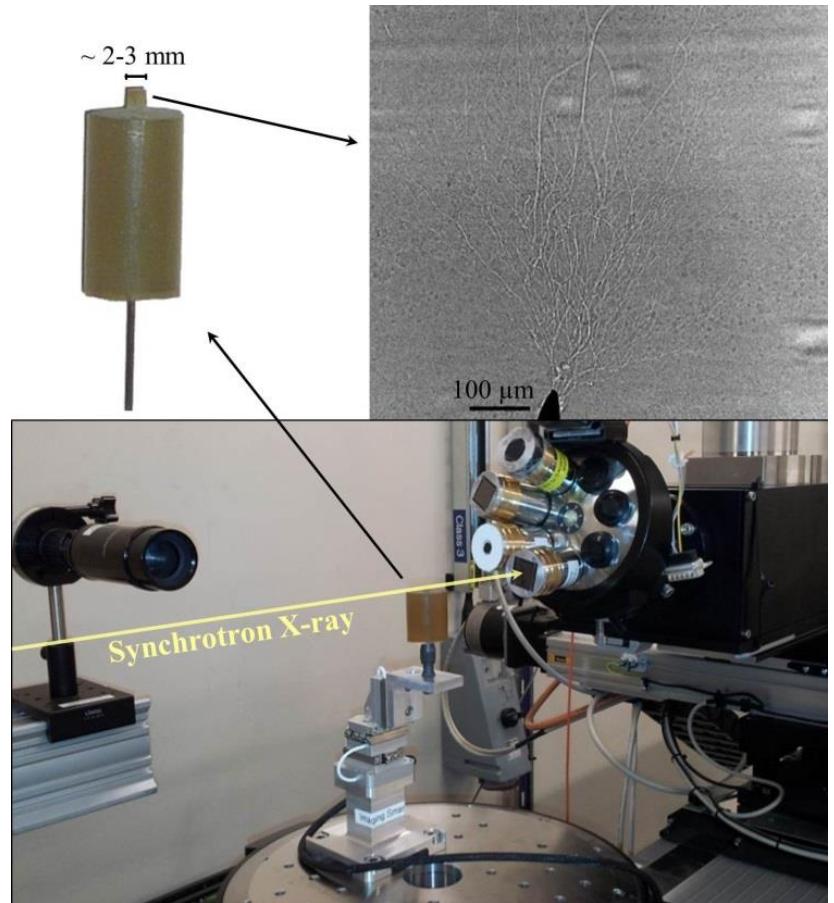


XCT Image Acquisition: Synchrotron

- X-rays at synchrotron: high intensity and coherent
- Diamond Light Source synchrotron, UK.



Ref.: <http://www.diamond.ac.uk/>

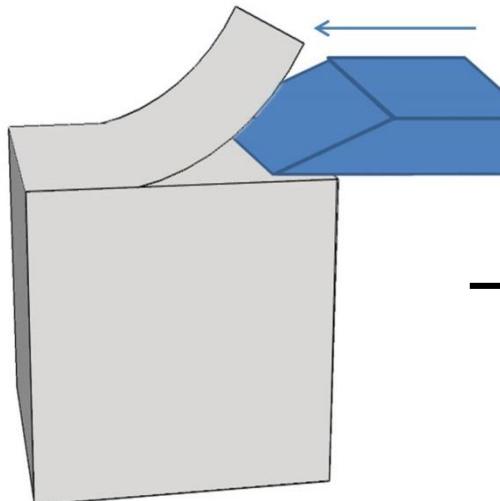


Experimental Procedure (3b)

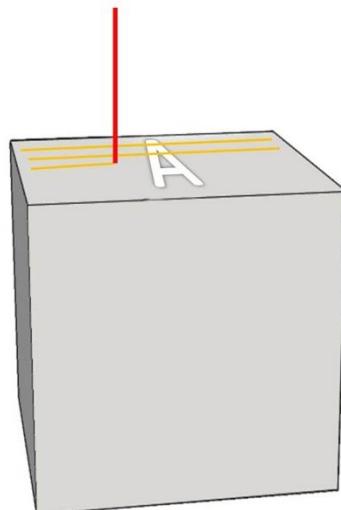


Serial Block-Face SEM (SBFSEM)

Slicing



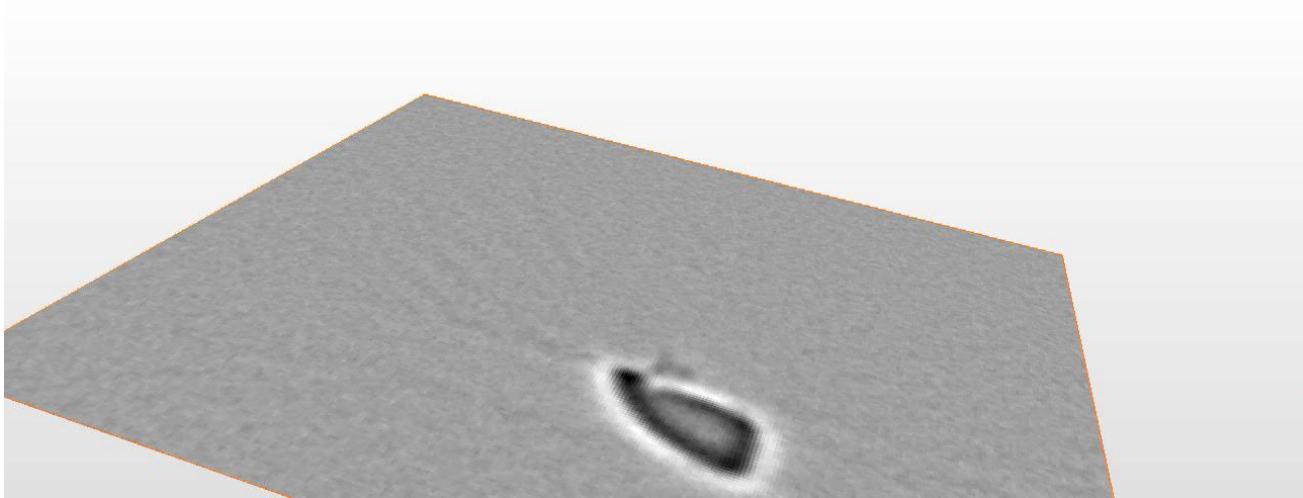
SEM Imaging



One Slice Imaged

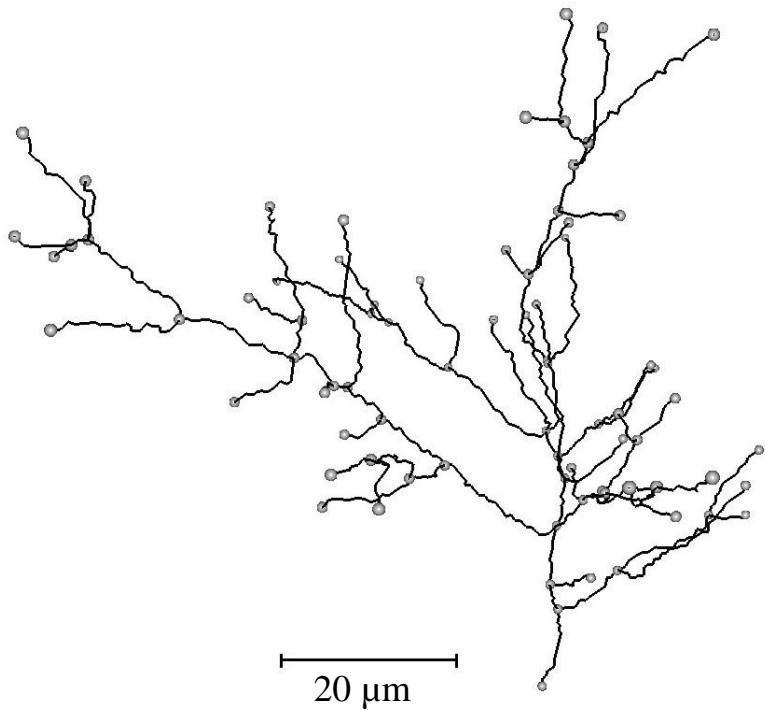
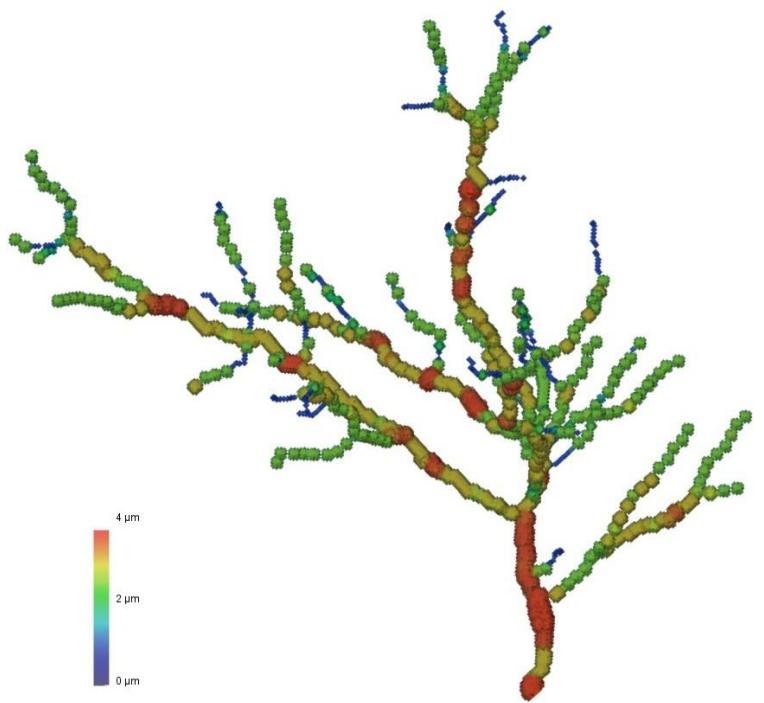


Experimental Procedure (4)



link

Experimental Procedure (5)



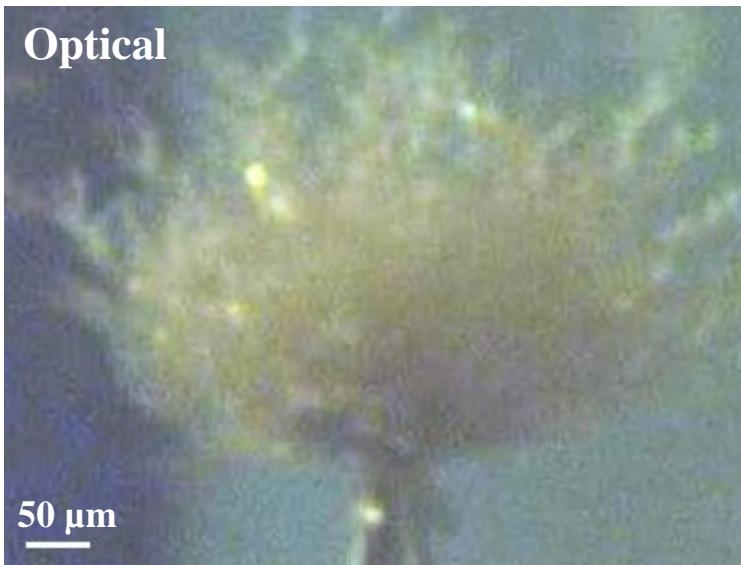
1. Background
2. Experimental description
- 3. Examples of 3D geometrical models**
4. Fractal dimension



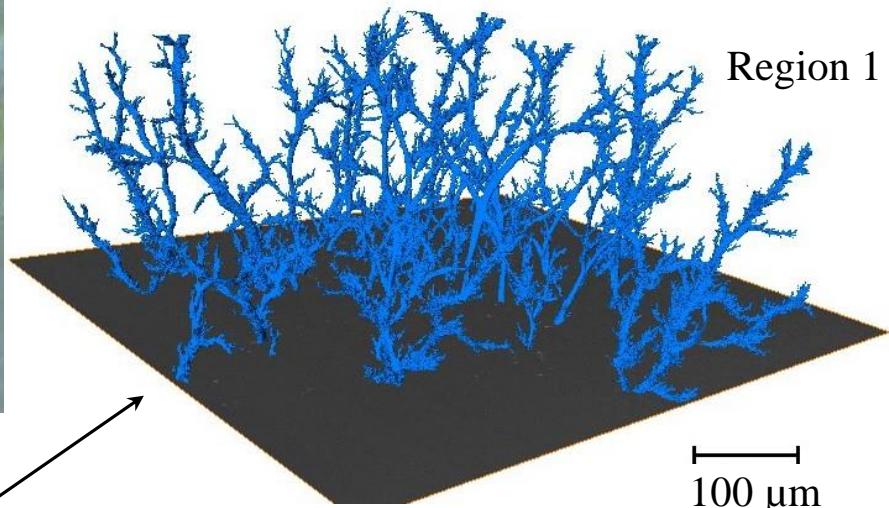
Algunos ejemplos de la data disponible

Sample 1

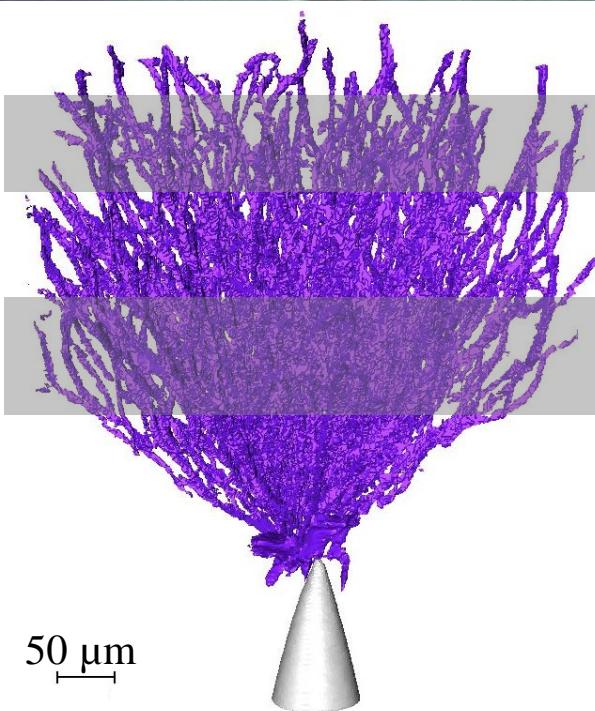
Optical



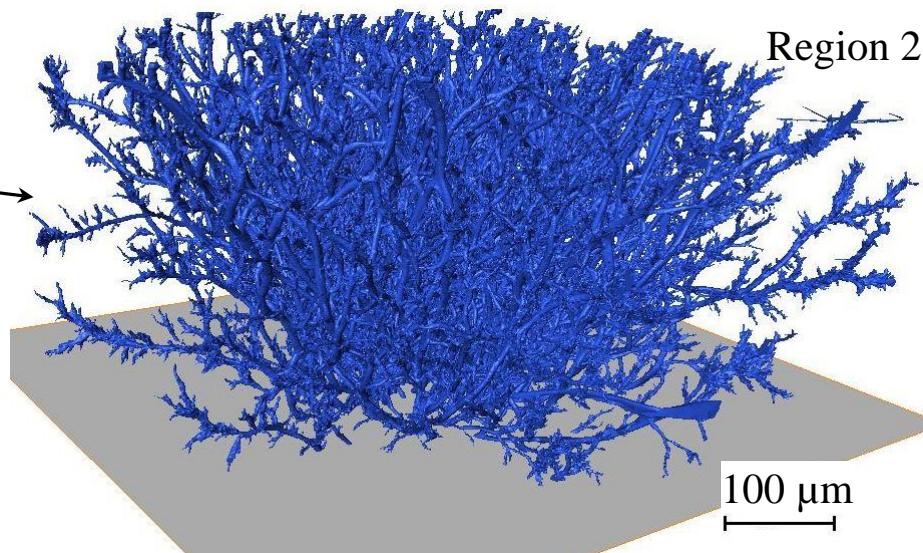
SBFSEM



XCT

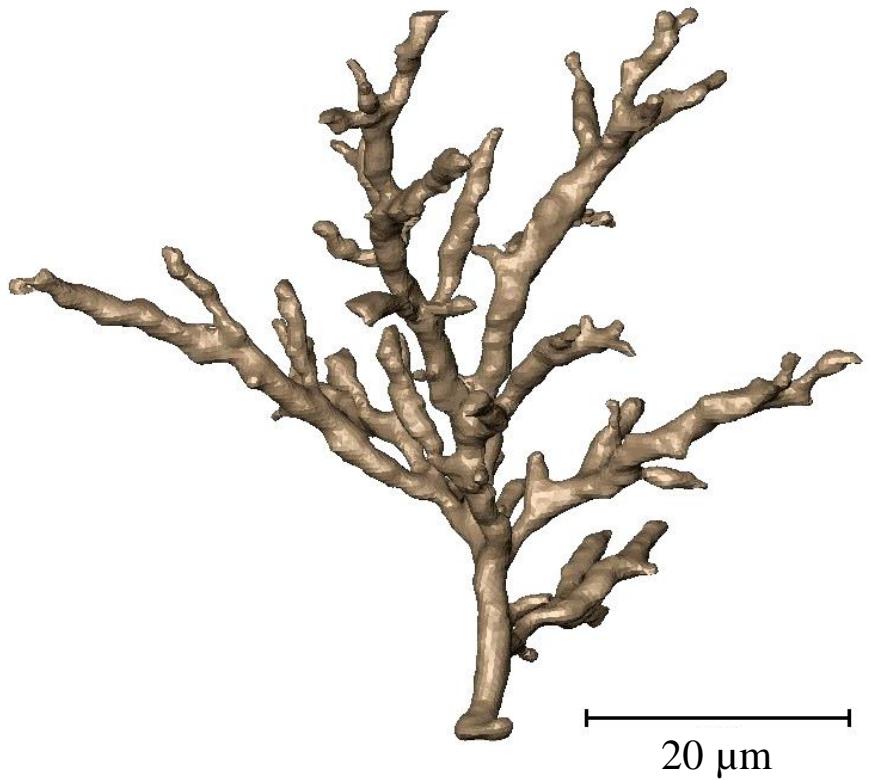


Region 2

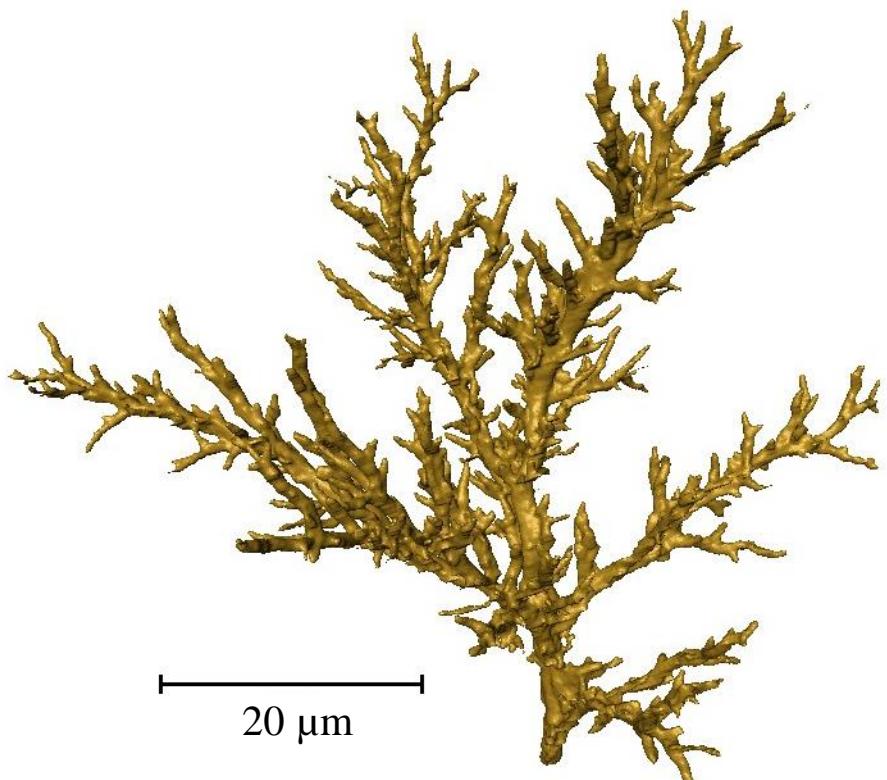


Sample 2

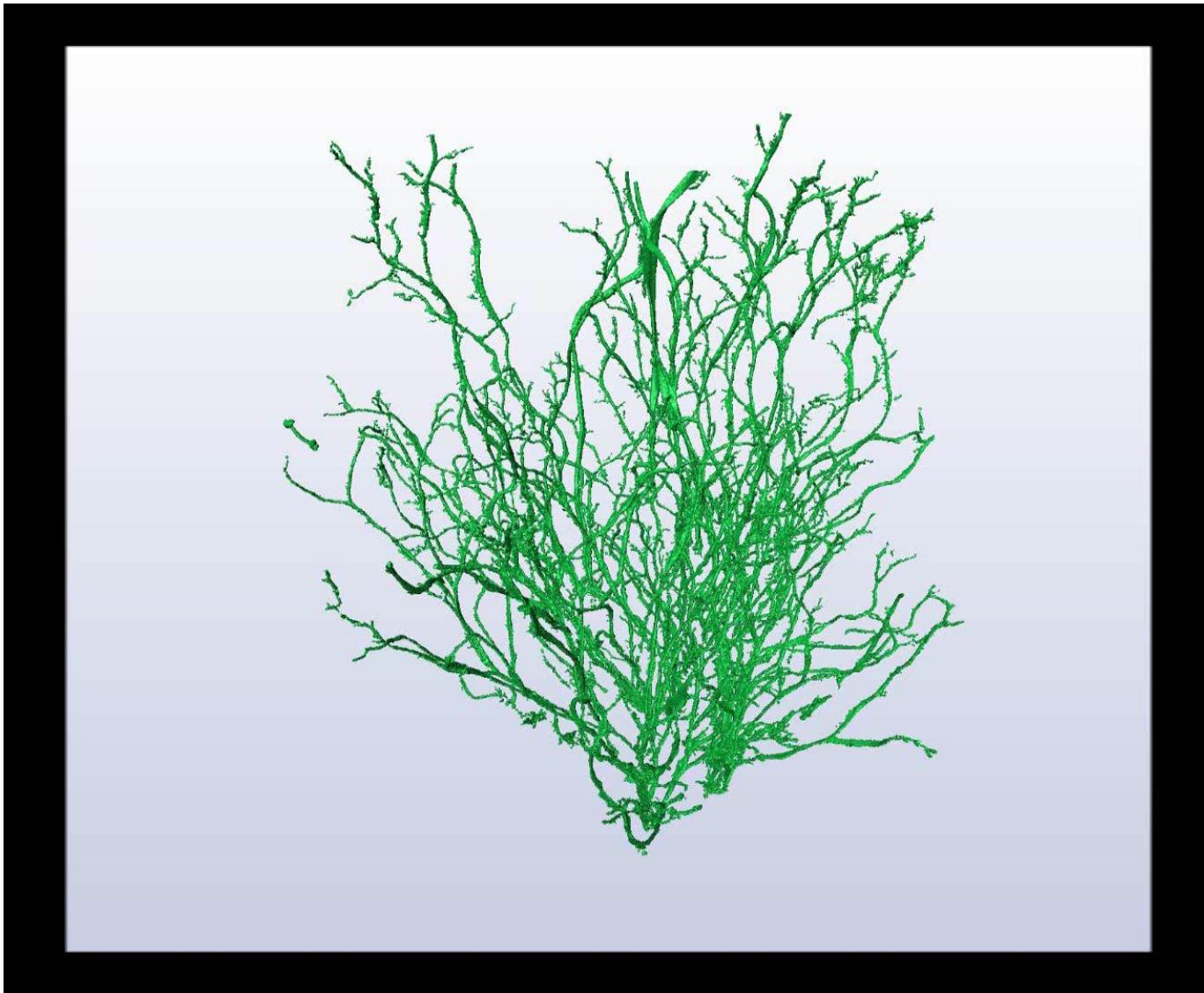
XCT (Laboratory)



SBFSEM



Sample 3 (animation)



link

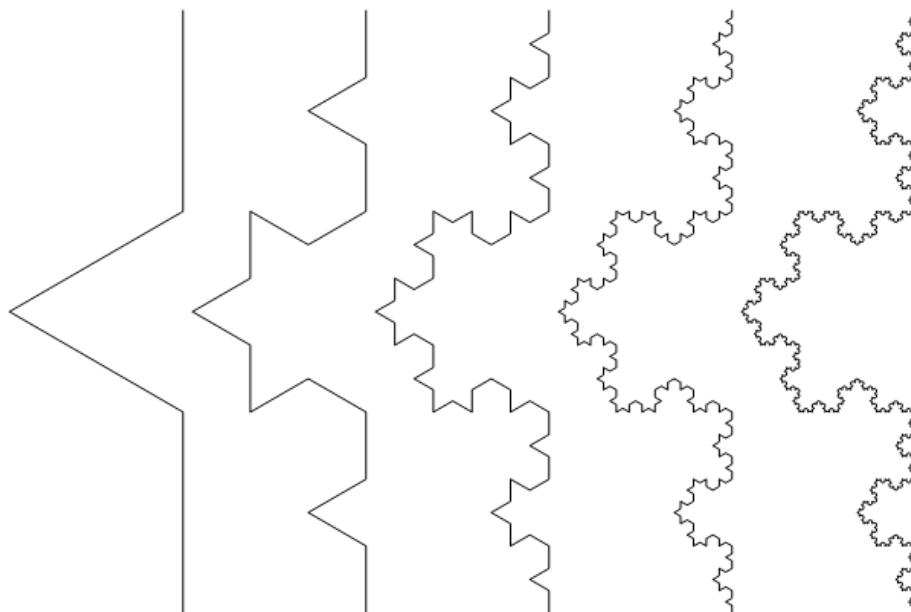


La data disponible es una pila de imágenes 2D ya segmentadas

1. Background
2. Experimental description
3. 3D geometrical model creation
4. Fractal dimension

Fractales

- Benoit Mandelbrot (1975)
- Estructuras geométricas que se repiten a sí mismo (“self-similarity” - autosimilar)
- Fractal matemático (curva de Koch) vs. fractal natural (línea costera, árboles, etc.)



Árboles eléctricos y dimensión fractal

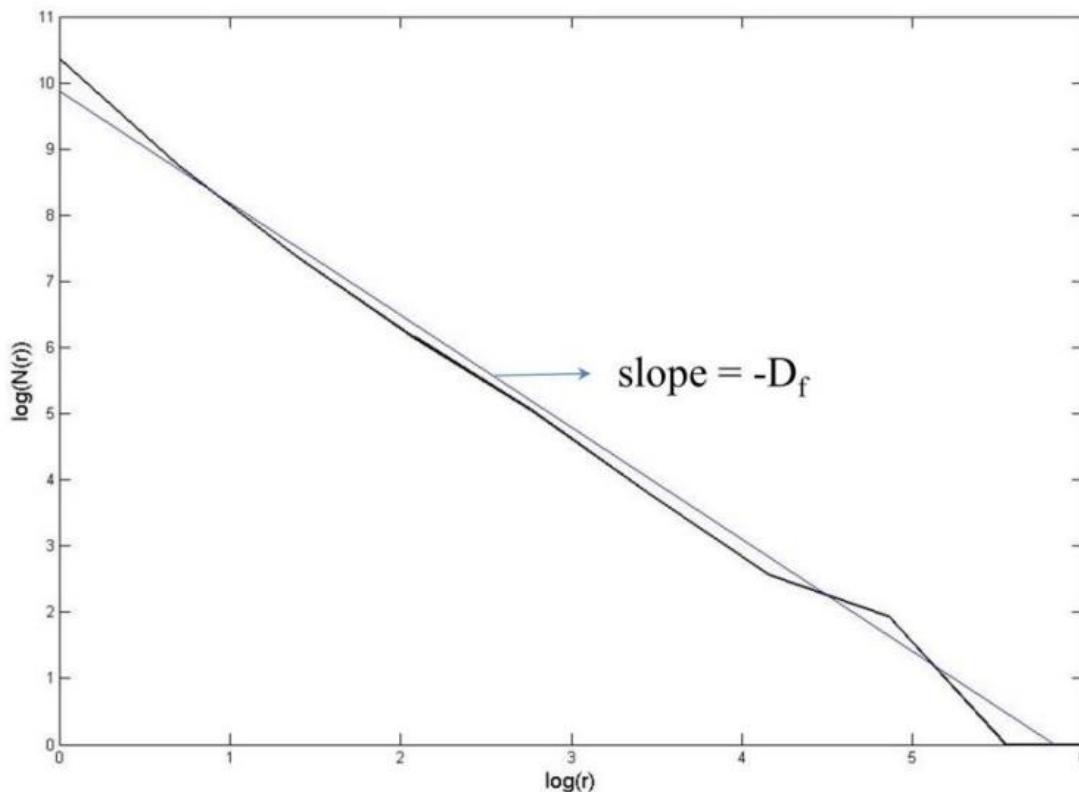
- Árboles eléctricos poseen estructura compleja que no es posible de describir analíticamente.
- La forma de los árboles eléctricos se describe a través de su dimensión fractal.
- Algunos modelos matemáticos de crecimiento de árboles eléctricos utilizan la dimensión fractal como uno de sus parámetros fundamentales.
- Árboles de dimensión fractal más pequeña crecen más rápido (son más peligrosos)

Cálculo de la dimensión fractal

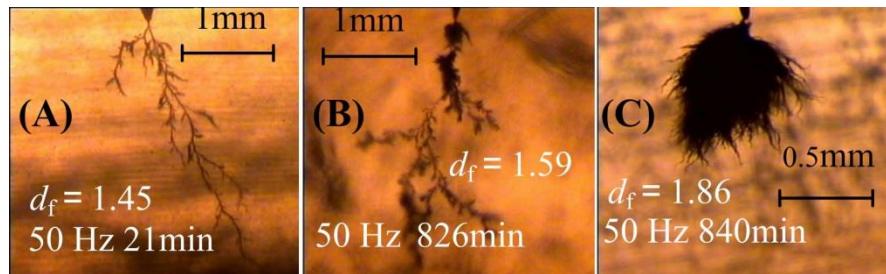
- Método de “box-counting”: el espacio es cubierto con “N” cubos de arista “r”.
- Se satisface relación

$$N(r) \propto r^{-D_f}$$

donde D_f es la dimensión fractal



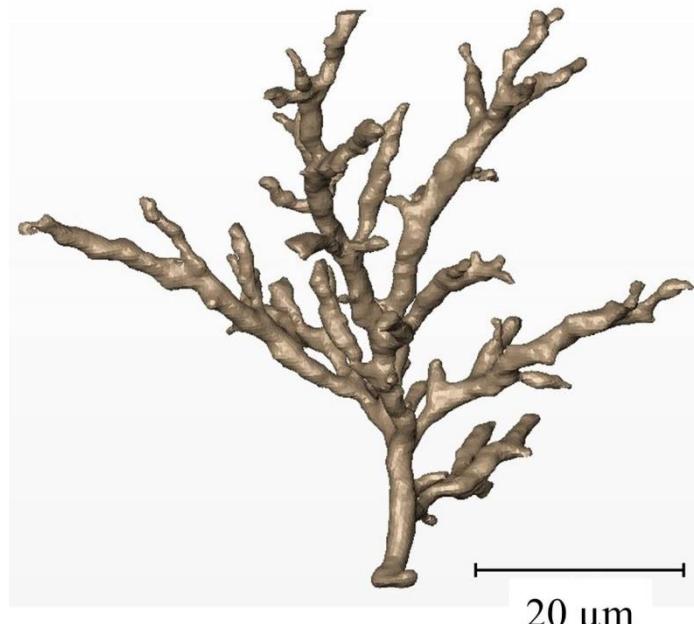
Fractal dimension



Z. Xiaoquan and G. Chen,
IEEE Trans. Dielectr. Insul., Vol. 15, pp. 800-807, 2008

3D Model

$${}^3\text{D} D_f = 1.69$$



2D Projections



$$xy \text{ } {}^2\text{D} D_f = 1.40$$



$$xz \text{ } {}^2\text{D} D_f = 1.42$$



$$yz \text{ } {}^2\text{D} D_f = 1.50$$

Algunas preguntas a investigar

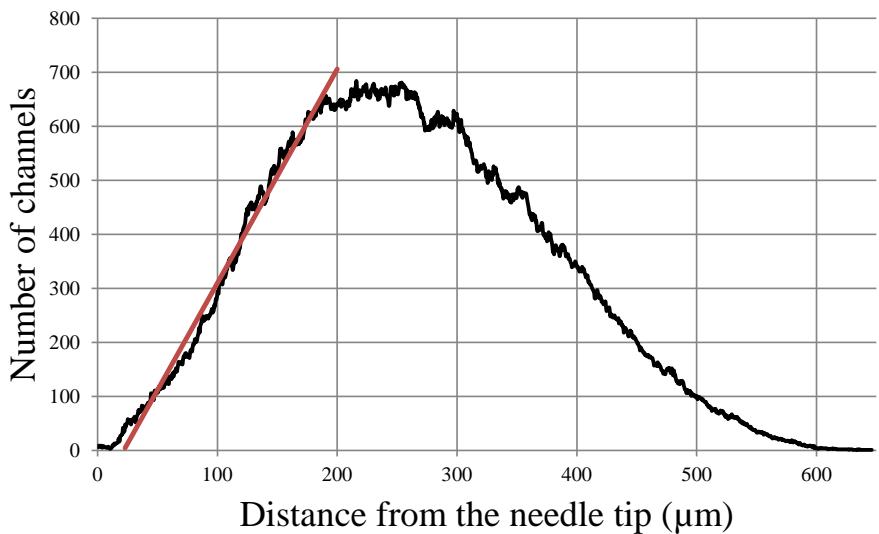
- ¿Son los árboles eléctricos estructuras que podemos categorizar como fractales?
- ¿Es la dimensión fractal el mejor parámetro que caracteriza la forma de un árbol eléctrico?
- ¿Cuál es el mejor método para la estimación de la dimensión fractal en árboles eléctricos?
- ¿Cuál es la relación entre la dimensión fractal estimada desde una imagen 2D y la del objeto real 3D?
- ¿En qué error estaban incurriendo los investigadores al estimarla desde imágenes proyectadas 2D?



Extra: Caracterización

Bush vs. Branch

Sample	U1	U2	U3
Description	Bush	Small branch	Low density bush
Mean Diameter (μm)	4.4	2.0	3.1
Volume/length (μm^2)	4,672	27	907
${}^{3D}D_f$ Fractal dimension	2.23	1.69	1.94
Number of nodes	5,040	78	6,768
Nodes/Length (μm^{-1})	13	1	9
Node density (μm^{-3})	2.8×10^{-3}	4.8×10^{-2}	1.0×10^{-2}
Mean Tortuosity	1.6	1.2	2.5



Number of channels slope:
 Bush-type: $\sim 3\text{-}10$ channels/ μm
 Branch-type: < 1 channel/ μm

Extensive characterisation

Sample	U1	U2	U3	U4	T.E.-T.G							
Instrument	micro-XCT(ν_1)	SBFSEM_R1	SBFSEM_R2	micro-XCT(ν_2)	SBFSEM	micro-XCT(synchro.)	micro-XCT(ν_2)	micro-XCT($\nu_2\text{-}40X$)	1st micro-XCT(ν_2)	2nd micro-XCT(ν_2)	2 _{imp} micro-XCT(ν_2)	
Global parameters	Pixel size (xy / z) (μm)	1.07	0.2/0.2	0.2/0.2	0.371	0.075/0.15	0.365	0.4535	0.2322	0.4535	0.4535	0.4509
	Slices used	356	1,273	1,567	160	456	2,300	1,589	461	176	1,333	1,434
	Length (μm)	381	255	313	59	68	839	720	107	80	605	647
	Diameter (μm)	4.4 (39%)	3.3 (45%)	4.5 (56%)	2.0 (18%)	1.0 (31%)	2.6 (37%)	3.1 (38%)	1.2 (28%)	2.6 (38%)	3.7 (37%)	2.5 (25%)
	Surface area (μm^2)	1.70×10^6			3.50×10^3	4.56×10^3	7.02×10^5	7.67×10^5	2.49×10^5	4.29×10^4	2.48×10^6	2.60×10^6
	Volume (μm^3)	1.78×10^6	4.51×10^5	3.94×10^6	1.62×10^3	9.97×10^2	4.96×10^5	6.53×10^5	6.72×10^4	2.50×10^4	1.95×10^6	1.59×10^6
	Conv. hull volume (μm^3)	5.06×10^7	7.41×10^7	1.09×10^8	5.62×10^4	7.26×10^4	5.48×10^8	2.25×10^8	5.68×10^5	1.67×10^5	7.83×10^7	1.03×10^8
	Surface/Volume (μm^{-1})	0.95			2.16	4.57	1.42	1.18	3.70	1.72	1.27	1.64
	Volume/length (μm^2)	4,672	1,769	12,588	27	15	591	907	628	313	3,227	2,453
	Prop. volume degraded	3.5%	0.6%	3.6%	2.9%	1.4%	0.1%	0.3%	11.8%	14.9%	2.5%	1.5%
Fractal	${}^{3D}\text{D}_f$	2.23			1.69	1.84	1.80	1.94	2.33	2.12	2.18	2.16
	$xy\ {}^{2D}\text{D}_f$	1.83			1.40	1.54	1.62	1.72	1.72	1.61	1.75	1.76
	$xz\ {}^{2D}\text{D}_f$	1.83			1.42	1.58	1.66	1.75	1.73	1.58	1.76	1.79
	$yz\ {}^{2D}\text{D}_f$	1.86			1.50	1.56	1.68	1.74	1.78	1.62	1.74	1.80
Skeleton	Number of nodes	5,040			78	504		6,768	28,967	927	21,121	23,028
	Number of segments	6,191			78	510		6,908	38,792	1,294	21,051	29,431
	End point fraction	0.2			0.5	0.5		0.4	0.1	0.2	0.3	0.3
	Node degree	3.2 (16%)			3.2 (12%)	3.1 (11%)		3.1 (9%)	3.4 (22%)	3.3 (20%)	3.1 (11%)	3.1 (10%)
	Segment length (μm)	17.3 (93%)			7.3 (60%)	3.0 (63%)		11.7 (118%)	2.3 (63%)	5.1 (60%)	8.8 (94%)	12.7 (86%)
	Tortuosity	1.6 (37%)			1.2 (6%)	1.2 (7%)		2.5 (38%)	1.5 (6%)	1.6 (11%)	1.6 (13%)	1.5 (12%)
	Branch angle (deg)	64 (47%)			69 (39%)	57 (48%)		63 (49%)	69 (46%)	67 (43%)	64 (47%)	60 (45%)
	Node density (μm^{-3})	2.8×10^{-3}			4.8×10^{-2}	5.1×10^{-1}		1.0×10^{-2}	4.3×10^{-1}	3.7×10^{-2}	1.1×10^{-2}	1.5×10^{-2}
	Seg. length/diameter	3.9			3.7	3.1		3.8	1.9	2.0	2.4	5.0

TEMA 2

La dinámica de las descargas parciales

Descargas parciales (DP)

Localised electric breakdown in electrical insulation



PDs deteriorate insulation



Catastrophic failure of electrical equipment

Measurement and analysis of PD

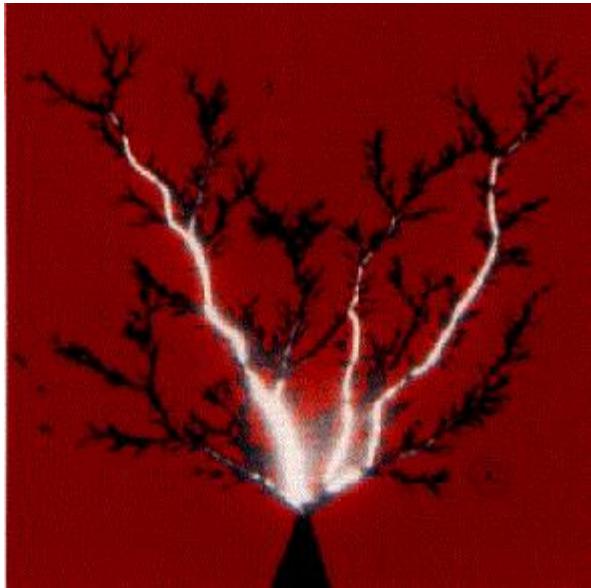


Diagnostic tool for *insulation condition assessment of electrical power equipment*

Equipamiento de potencia

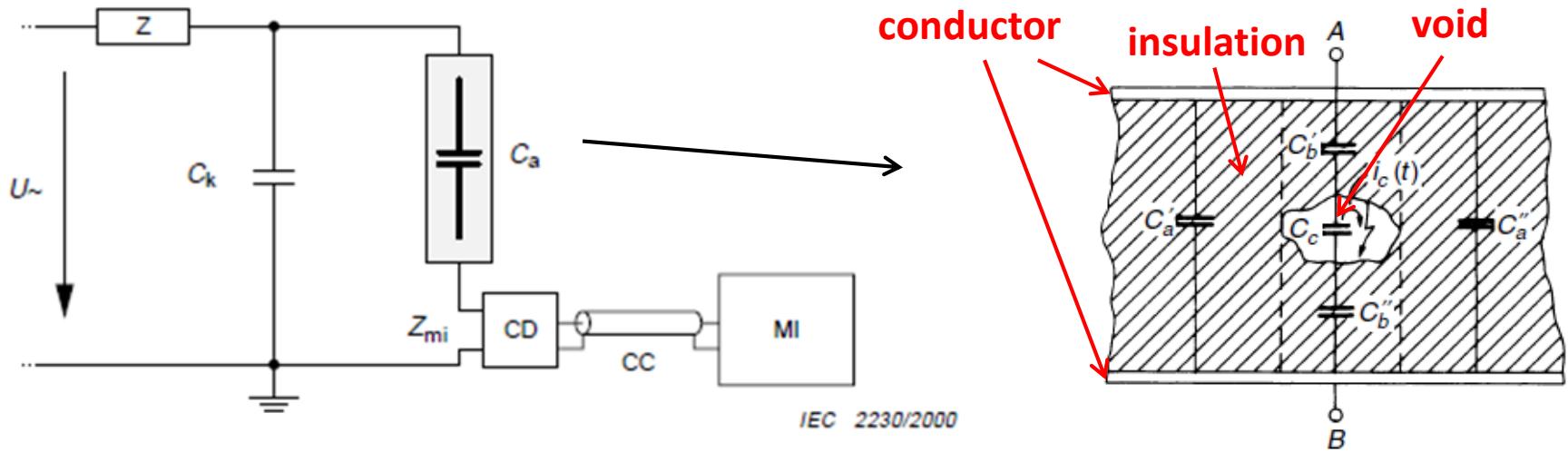


Árbol eléctrico y descarga parcial



Las DP se pueden medir...

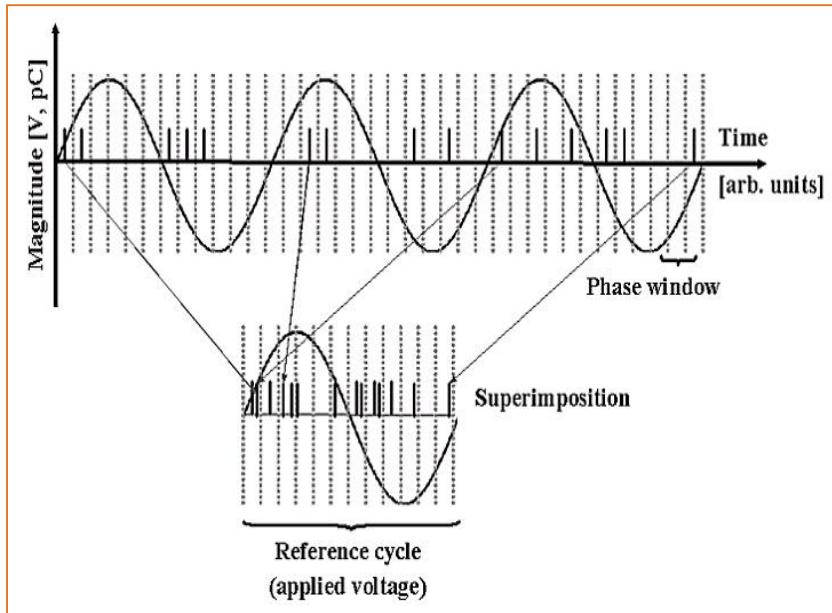
- Partial Discharge test circuit according standard IEC 60270



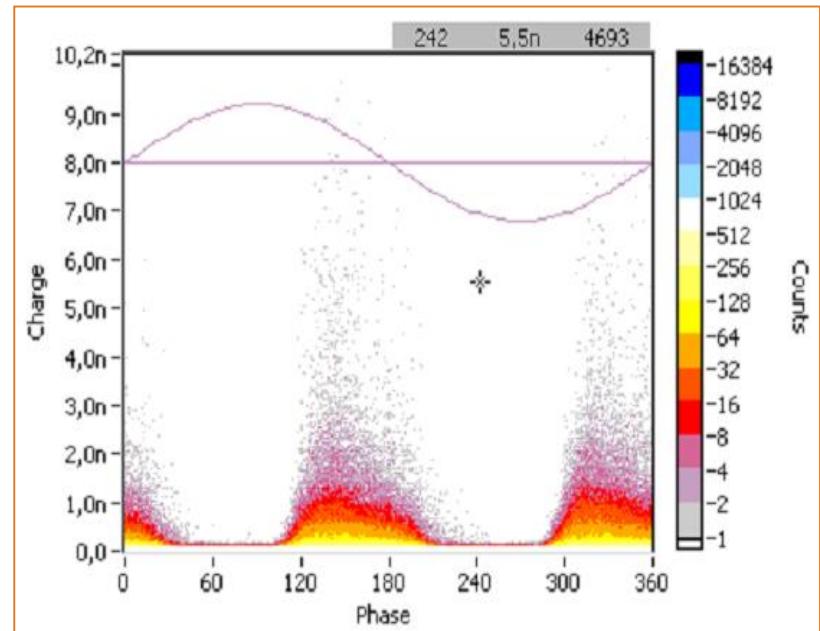
- Electric detection of the PD current pulse.

Análisis tradicional de DP

- PD process: stochastic phenomenon
- Analysis: statistics



Superimposition problem



Phase resolved plot

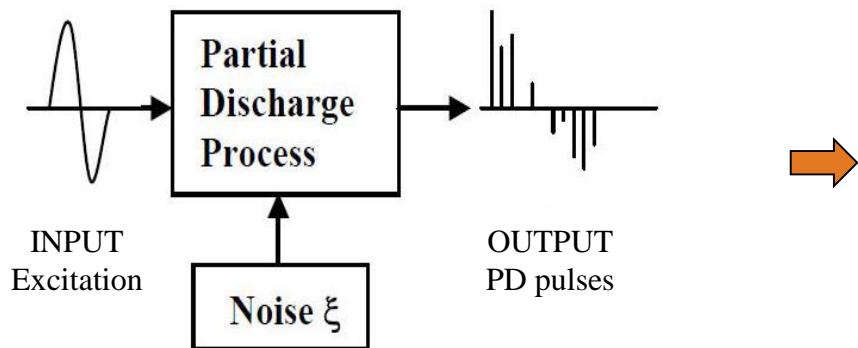
Disadvantage

- Does not consider the dynamics in the PD process

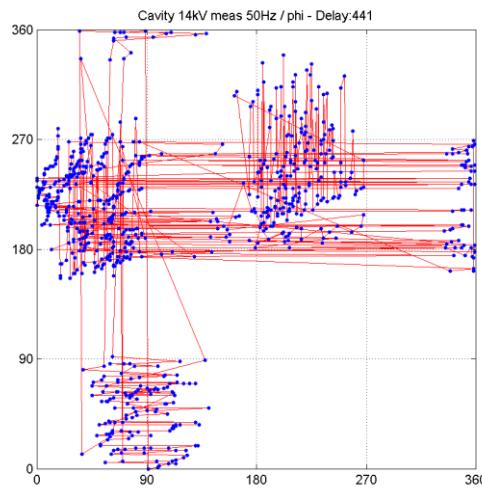
Análisis alternativo (propuesto)

- Proceso DP: Sistema dinámico no lineal, princ. determinístico
- Análisis: series de tiempo no lineal & teoría del chaos

Input-Output model

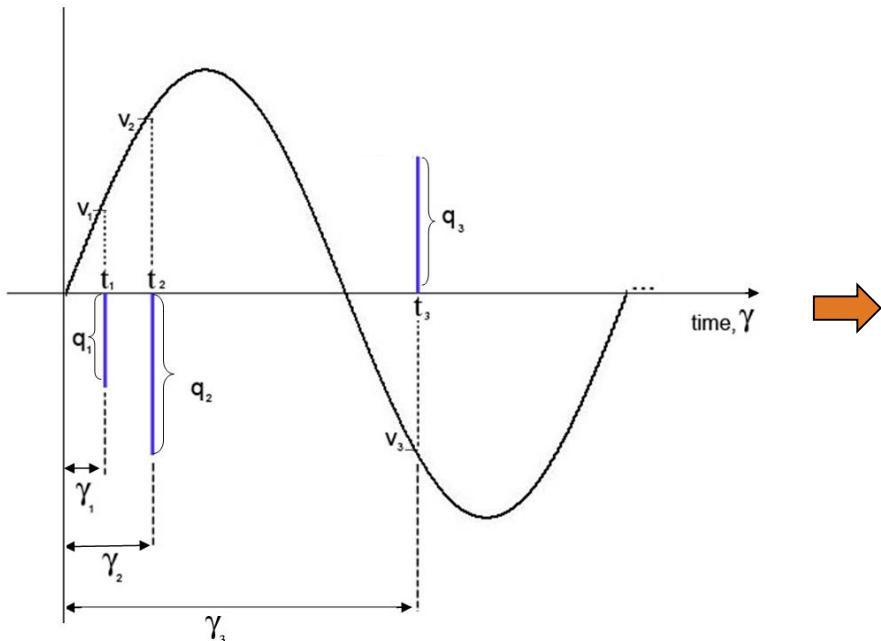


Trajectory



Data disponible

- PD data resolved in time
- Acquire for each discharge: time, PD magnitude, instantaneous voltage and phase angle of the applied voltage.



Time series

#	time	PD magn	voltage	phase angle
1	t_1	q_1	v_1	γ_1
2	t_2	q_2	v_2	γ_2
.
.
.
n	t_n	q_n	v_n	γ_n

Trasfondo teórico (1): Trayectorias

- Analysing the system dynamics → phase-space representation (“trajectory”)
- *Reconstruction of the phase-space* → one observable variable



delay coordinate embedding

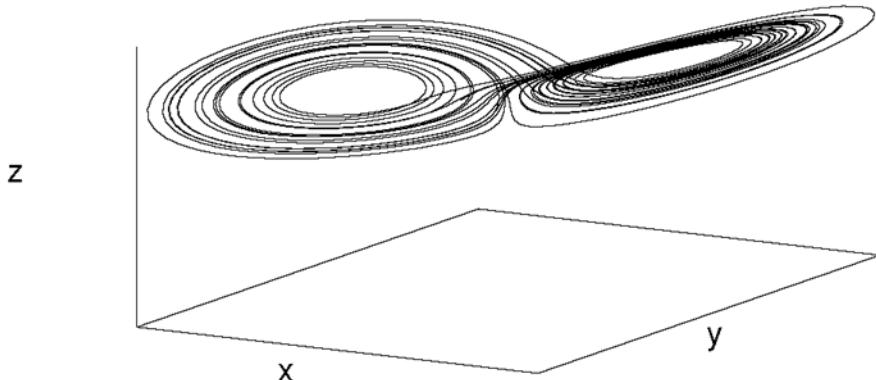


Selection of:

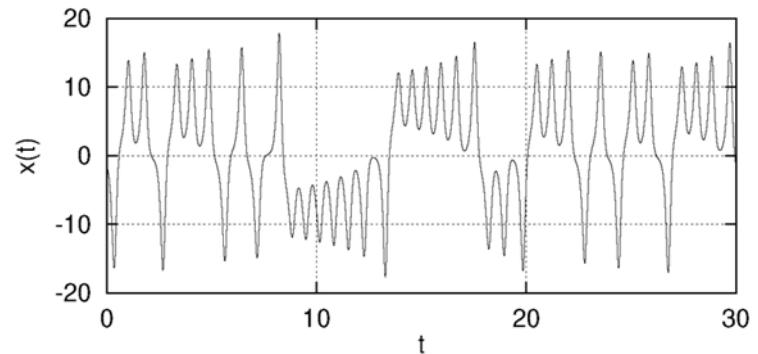
1. Variable
2. Embedding parameters
 - ✓ Dimension
 - ✓ Delay

Trasfondo teórico (2): Trayectorias

- Example: Lorenz attractor reconstructed from a time series

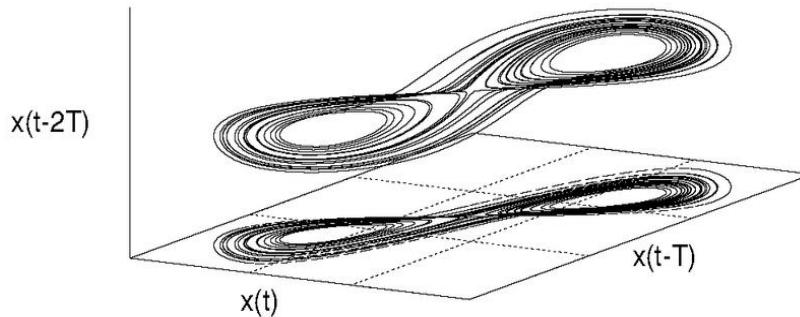


1. Original trajectory x, y, z



2. One variable: Time series $x(t)$

Embedding parameters:
✓ Delay: T
✓ Dimension: 3



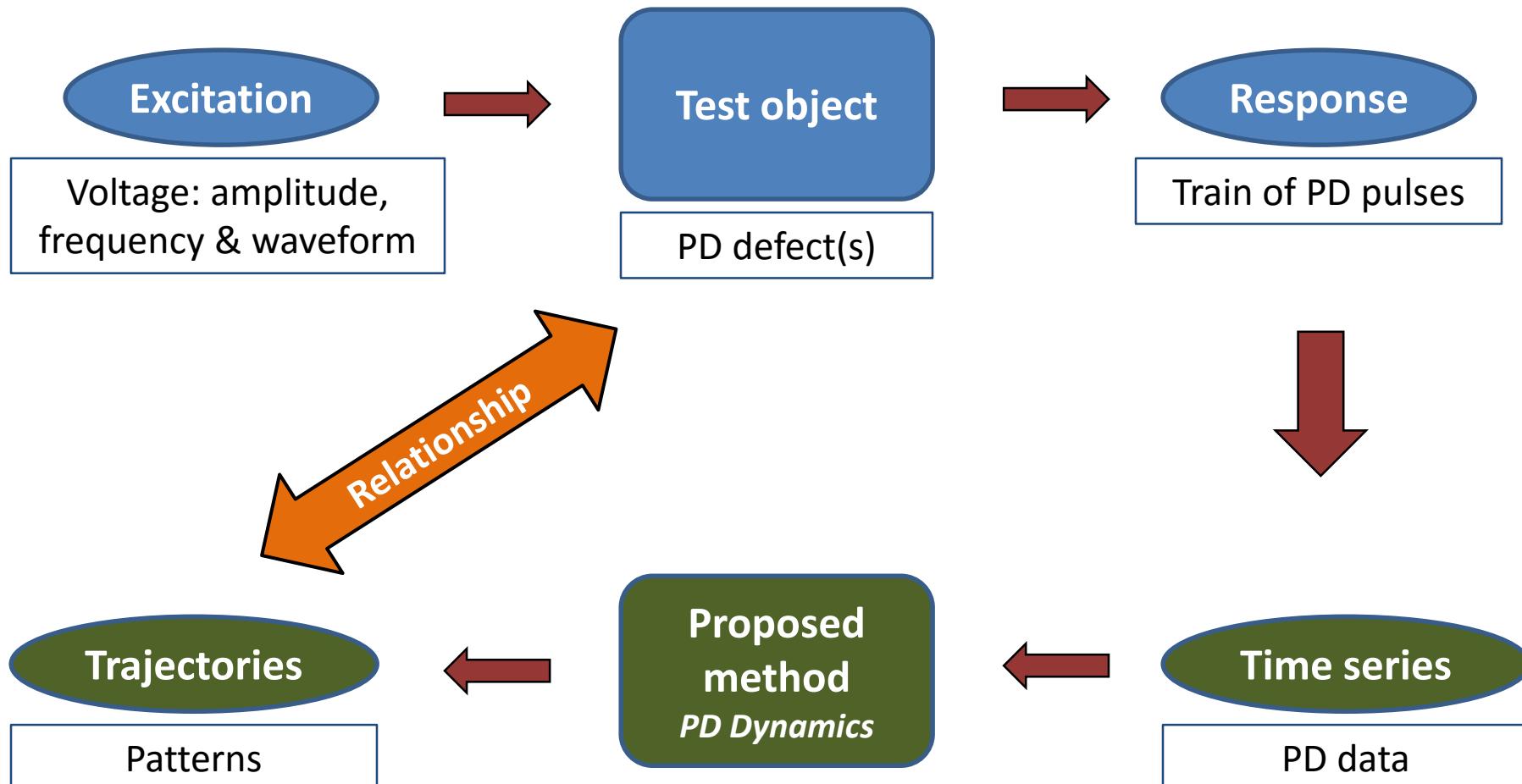
3. Reconstructed trajectory $x(t), x(t-T), x(t-2T)$

Objetivos del estudio

GRAL: Estudiar el comportamiento dinámico de las DP

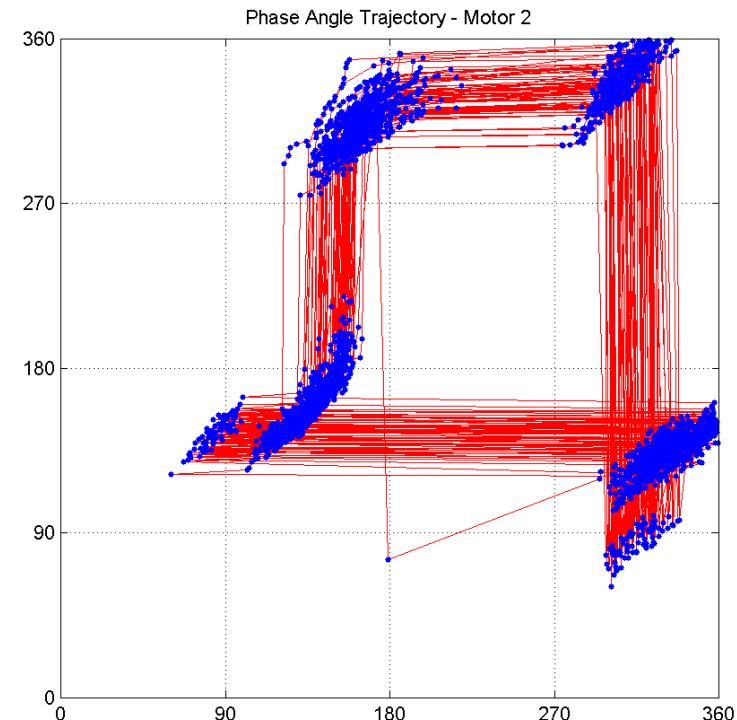
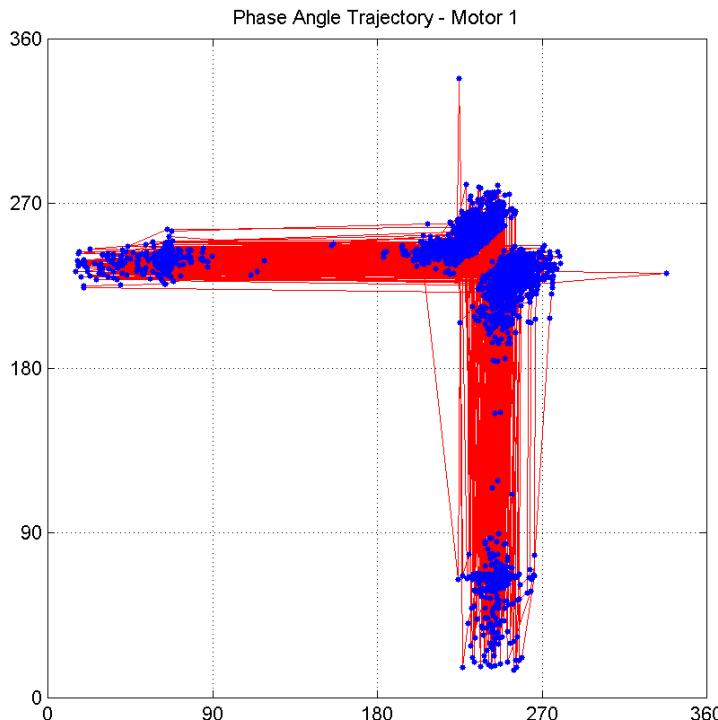
- Relacionar defectos de DP con patrones de DP
- Evaluar la potencialidad del método propuesto
- Evaluar la capacidad del método para:
 - Identificar fuentes de DP simultáneas
 - usarlo para el diagnóstico del envejecimiento del aislamiento eléctrico

Metodología



Caso estudio 1

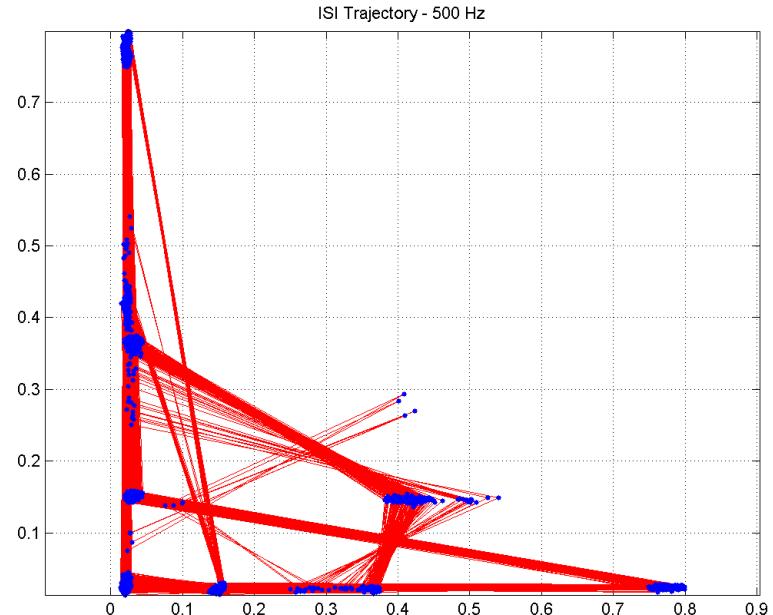
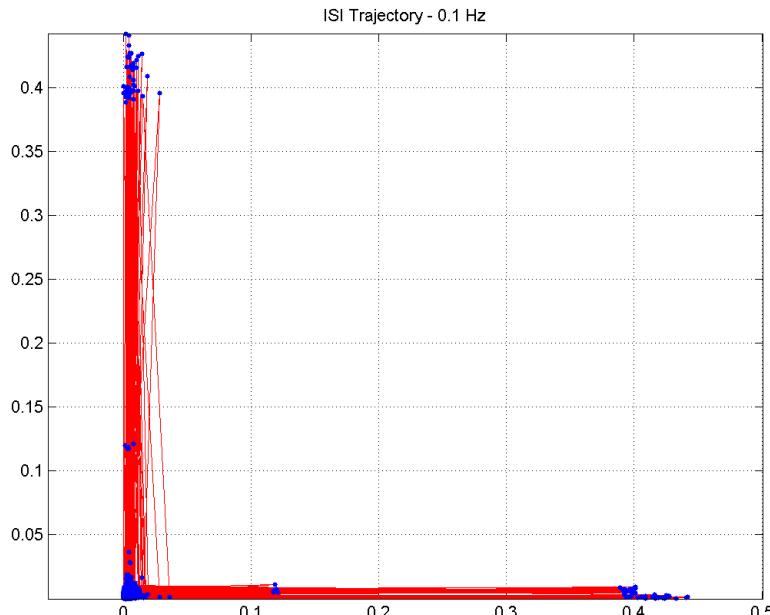
Trajectories for different test objects



Excitation: 50Hz sinusoidal
Test object: Motor 1 & 2
Variable: phase angle
Delay: 10

Caso estudio 2

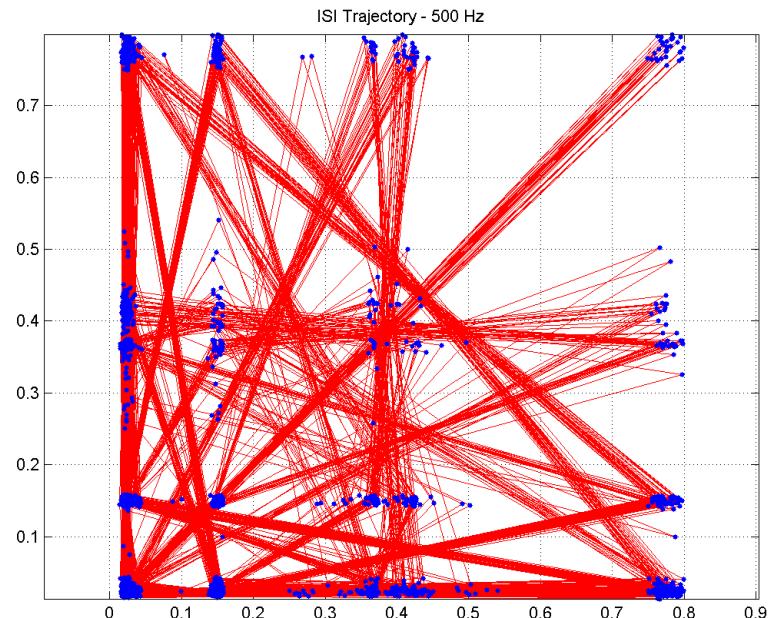
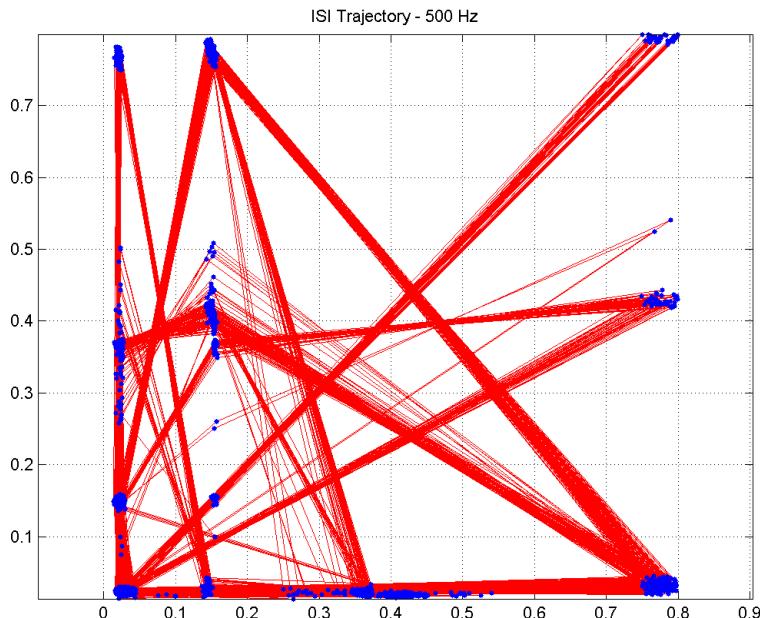
Trajectories for different frequencies of the applied voltage



Excitation: 0.1 & 500Hz sinus.
Test object: point-to-plane
Variable: ISI
Delay: 2

Caso estudio 2 (cont.)

Sensitivity to embedding parameter: delay

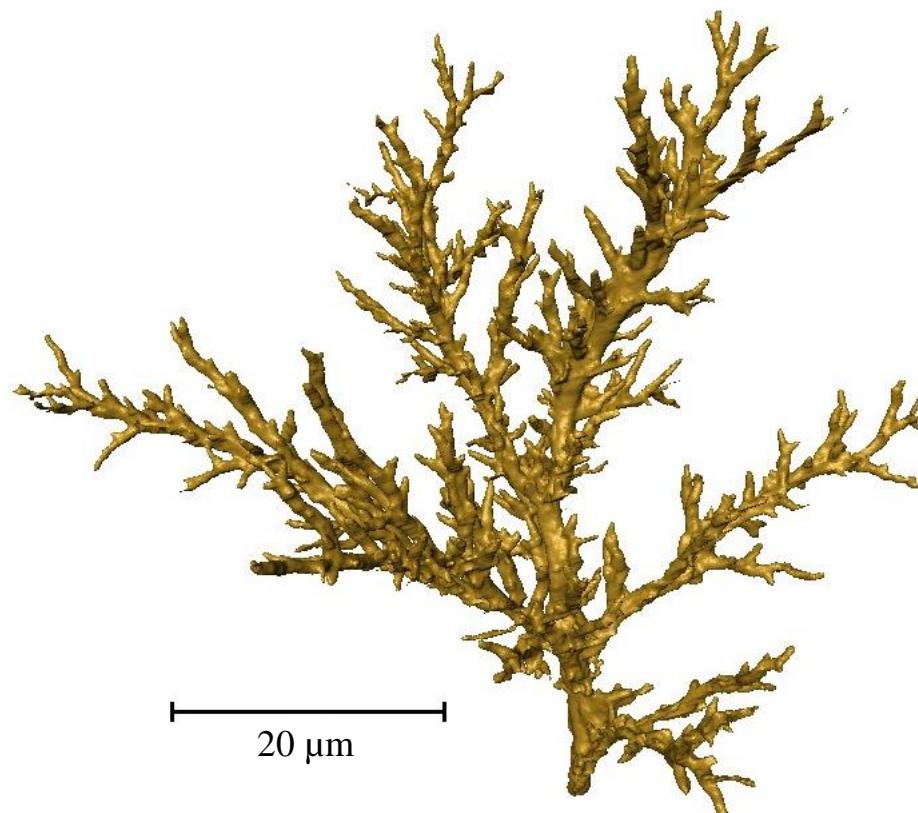


Excitation: 500Hz sinusoidal
Test object: point-to-plane
Variable: ISI
Delay: 4 & 81

Algunos temas a tratar

- Analizar si el proceso de DP es un sistema dinámico de carácter determinístico-caótico.
- Explotar las herramientas de análisis de la teoría de sistemas dinámicos no lineales, para identificar patrones de DP que informen sobre el tipo de defecto.
- Explorar la caracterización de patrones a través de trayectorias.
- Proponer el enfoque del análisis del proceso que permita mejorar el conocimiento de las DP y por ende, mejore el diagnóstico del estado del aislamiento eléctrico.

Gracias por su atención





Extra slides

Moulds for sample preparation

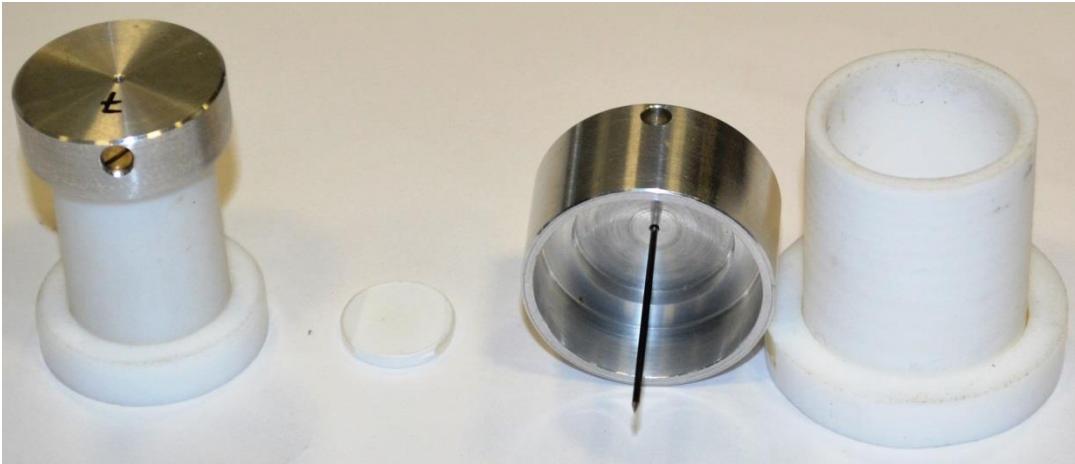
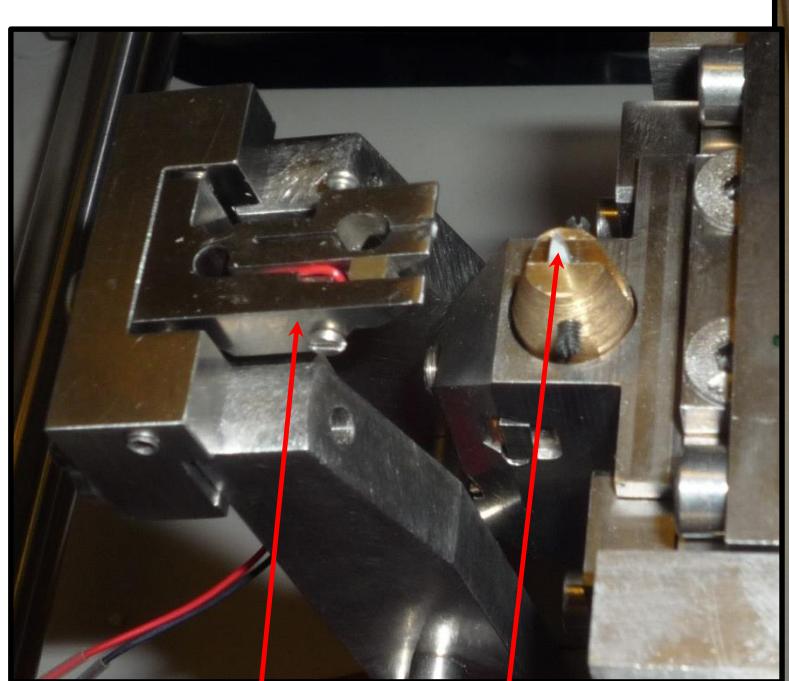
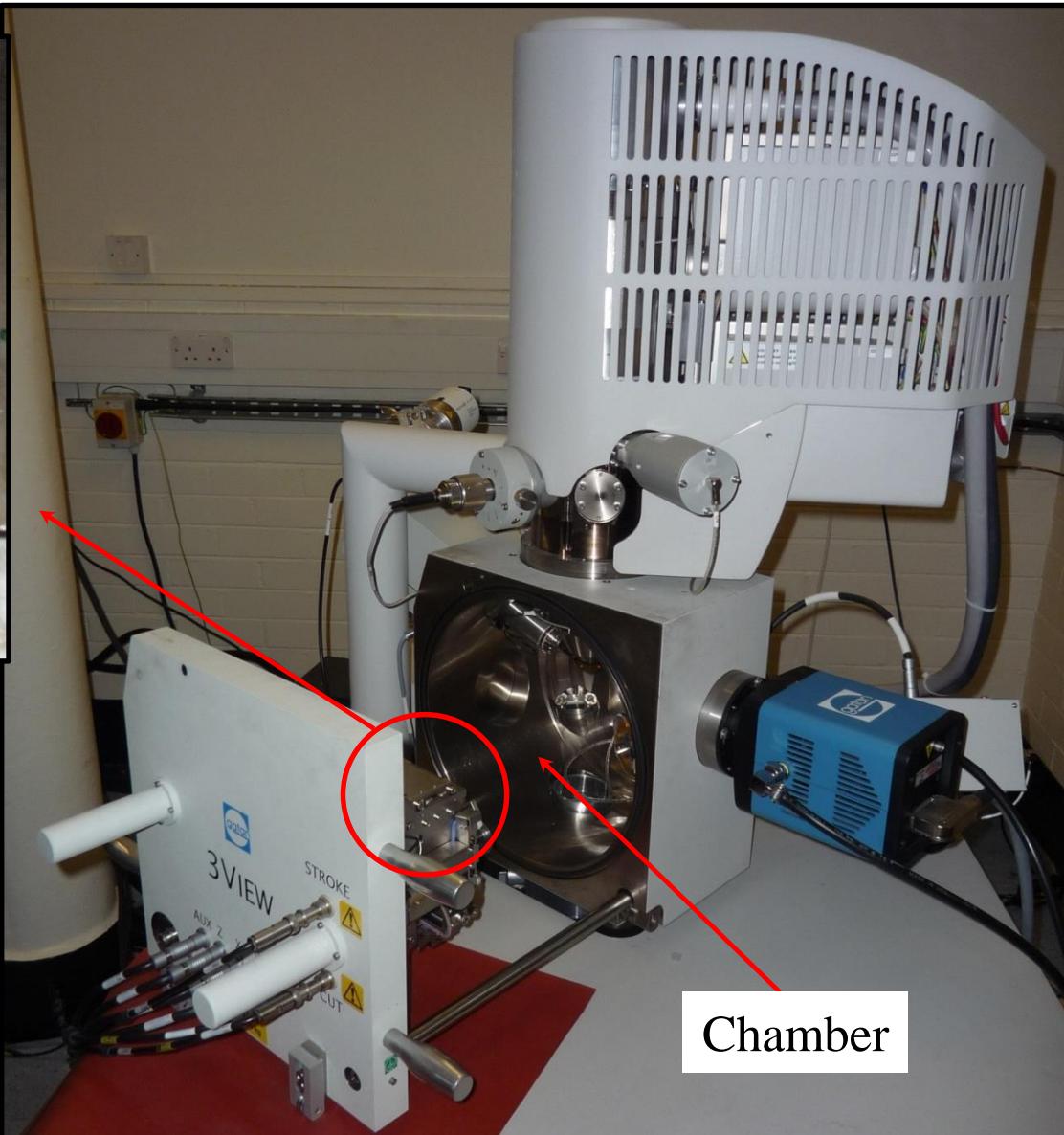


Image Acquisition (2): SBFSEM



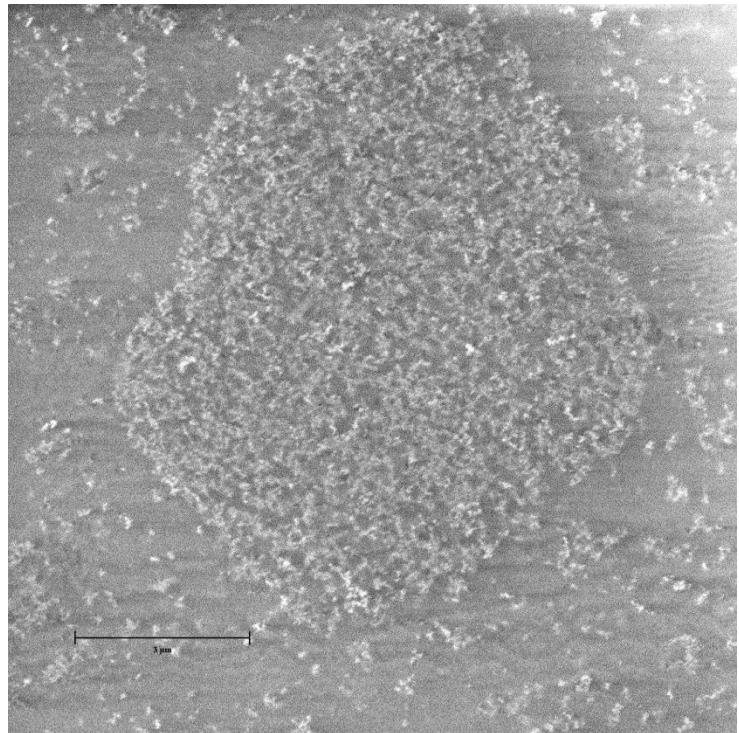
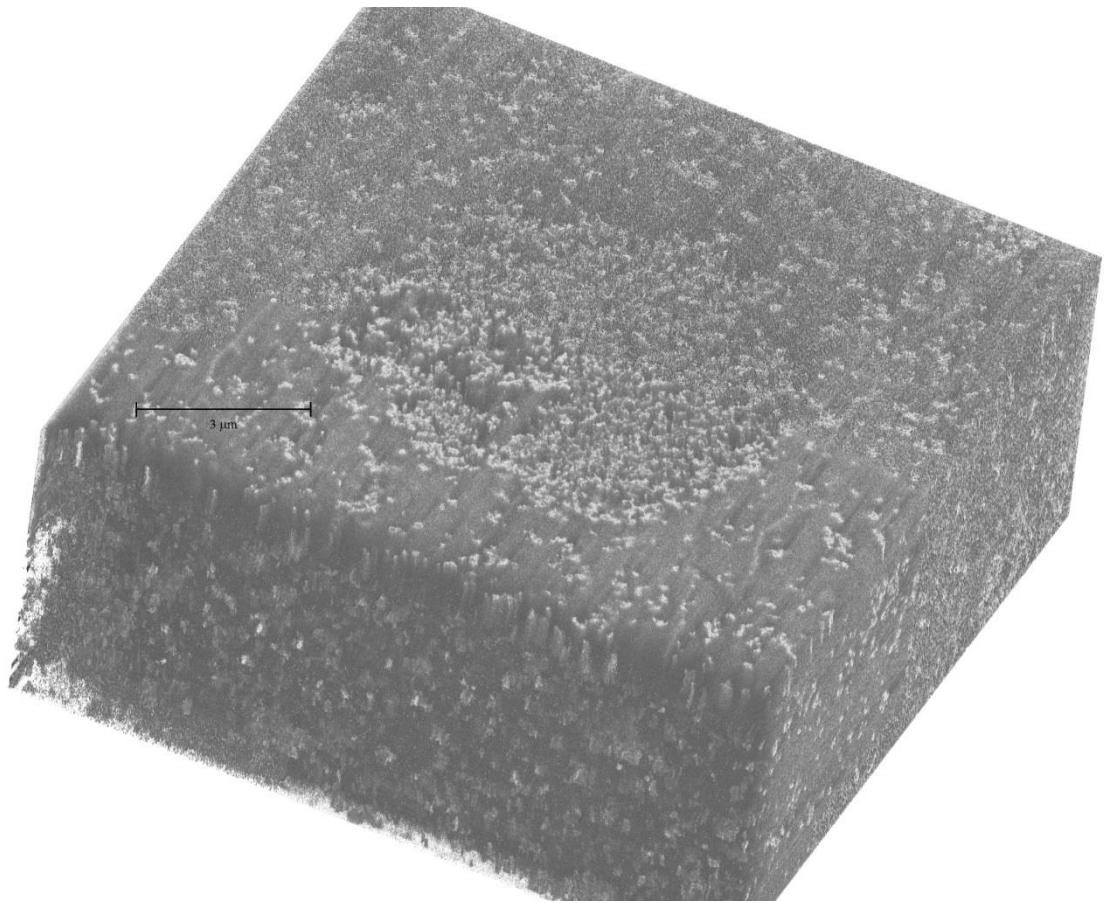
Knife

Sample

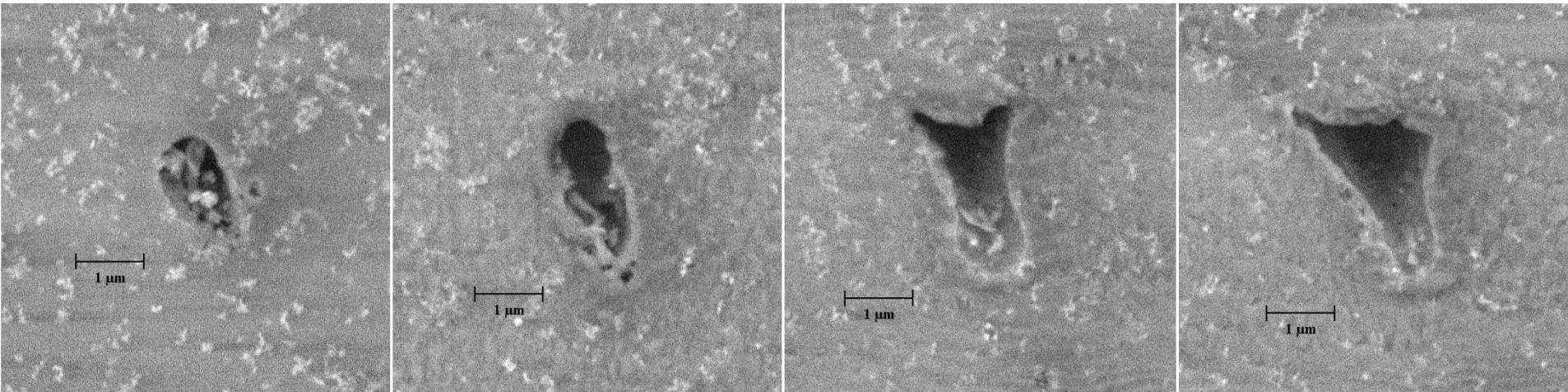


Chamber

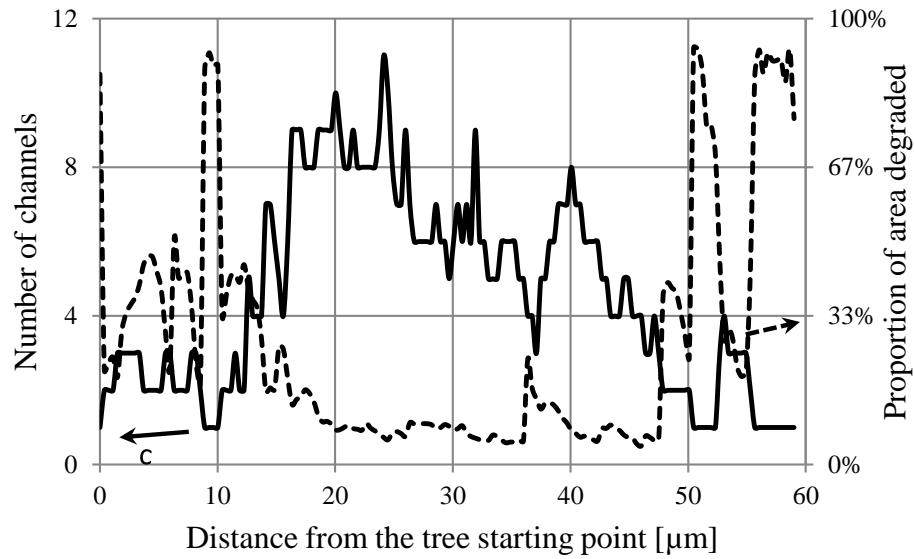
Agglomeration nano filled 3 wt% samples



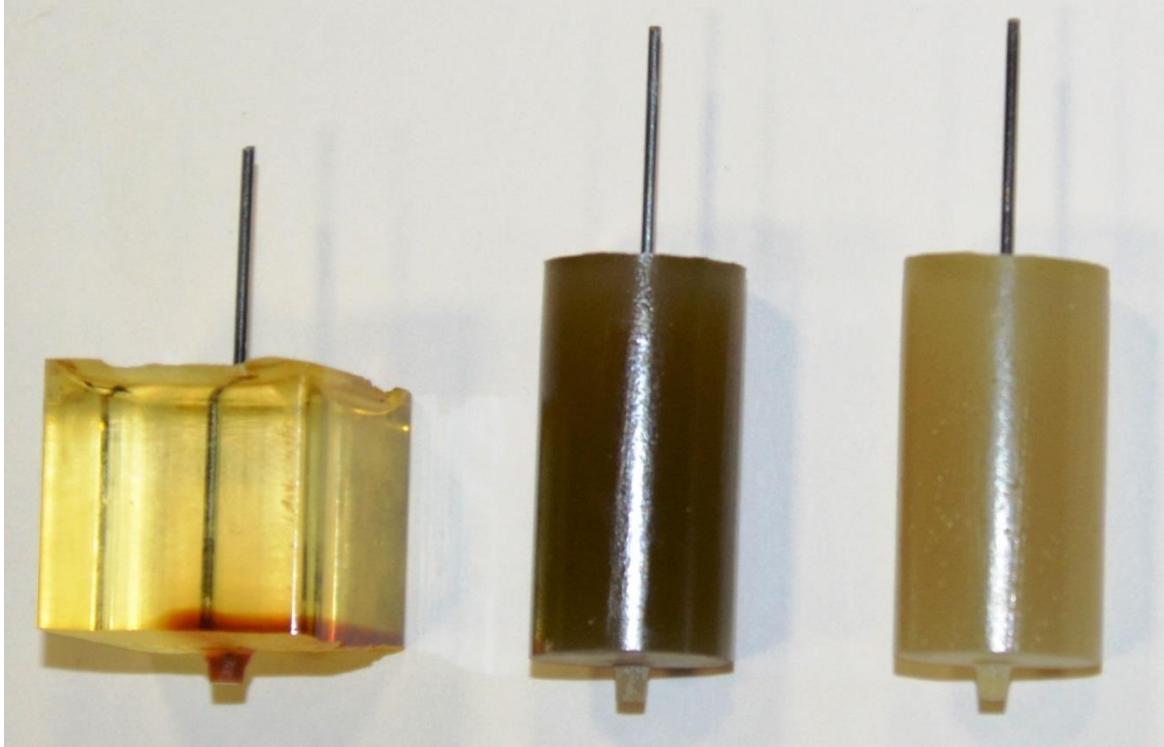
Slices of electrical tree channels in nano filled 3 wt% sample



Characterisation of 3D electrical trees



Preparation for imaging





End

UNIVERSIDAD TECNICA
FEDERICO SANTA MARIA