Optical sensing for the vectorial analysis of ultra-wideband electric field

requirements, performances and applications

Gwenaël GABORIT

Involved entities

Université Savoie-Mont-Blanc

- 3 locations (Chambéry, Le Bourget-du-Lac, Annecy)
- 19 laboratories
- 14 000 students

IMEP-LAHC Laboratory

- 2 locations (Grenoble, Le Bourget-du-Lac)
- Activities in 3 thematics (CMNE, RFM, PHOTO)
- 57 (13) researchers
- 17 (1) ingeneers & technicians
- 69 (4) PhD students and post-doc

Kapteos S.A.S.

- Created in 2009
- Market segments :
  → Scientific
  → Healthcare
  → Energy
- manpower: 10 workers

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→ Solutions provider and manufacturer of measurement instruments for research & industry in **harsh environment**

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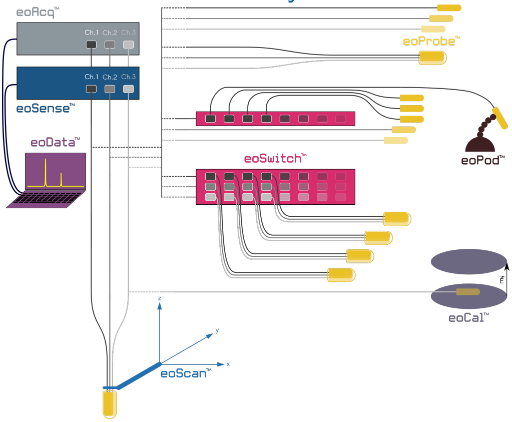
→ Some of our references:

- Private compagnies:
- Public institutes:

KAPTEOS S.A.S

→ State of the art EM measurement system

→ Comprehensive measurement system



Outline

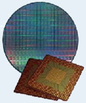
Outline

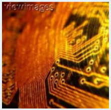
1. Introduction
2. Electro-optic technique
3. Applications
4. Conclusions

Context

Need of tools for the comprehensive characterization of the E-field

Circuits | EMC | Antenna | Healthcare | Energy





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Need of tools for the comprehensive characterization of the E-field

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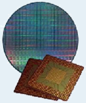

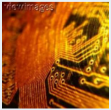

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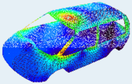

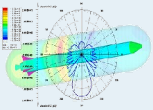

Antenna

Healthcare

Energy

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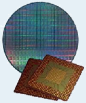

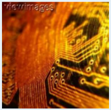

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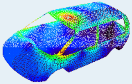

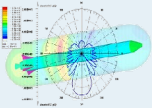

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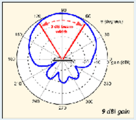

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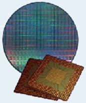
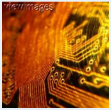

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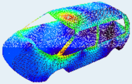
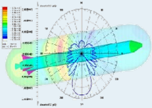

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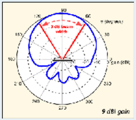

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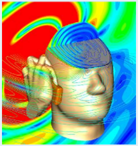

Energy

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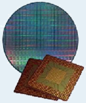

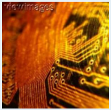

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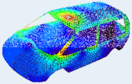

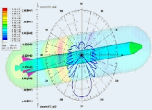

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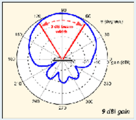

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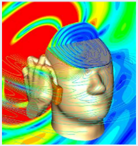

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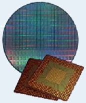
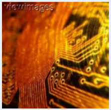
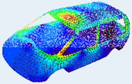
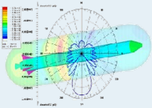
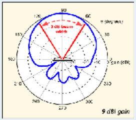
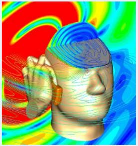
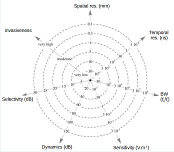
 	 	 	 	 

➡Measurement of the E-field **UWB**, **non-invasive**, **vectorial** and offering **appropriate spatial and time resolution**

Existing technologies

Scale



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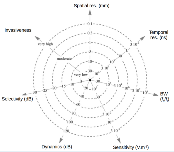
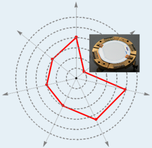


Bolometer



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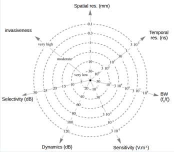

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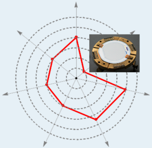
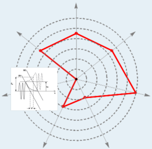


Franz-Keldysh



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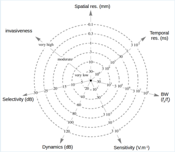

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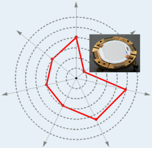

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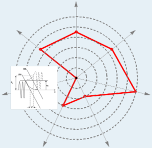
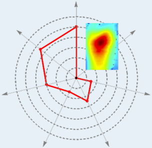


IR thermography



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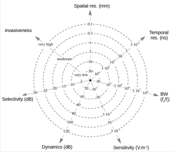

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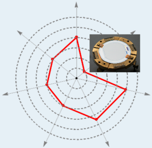

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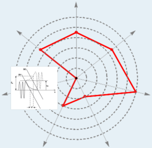

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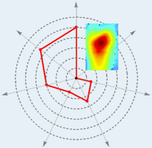
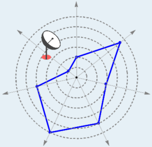


Antenna



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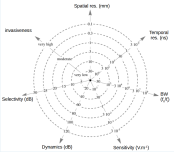

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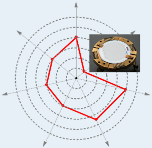

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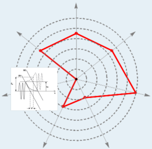

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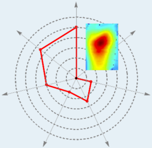

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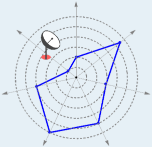
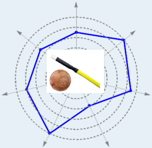


EO sensor



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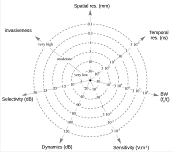

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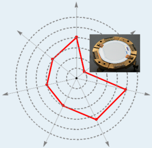

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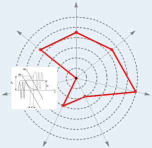

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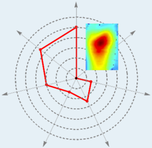

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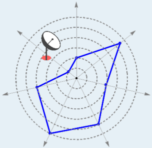

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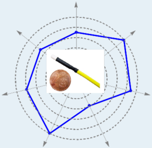
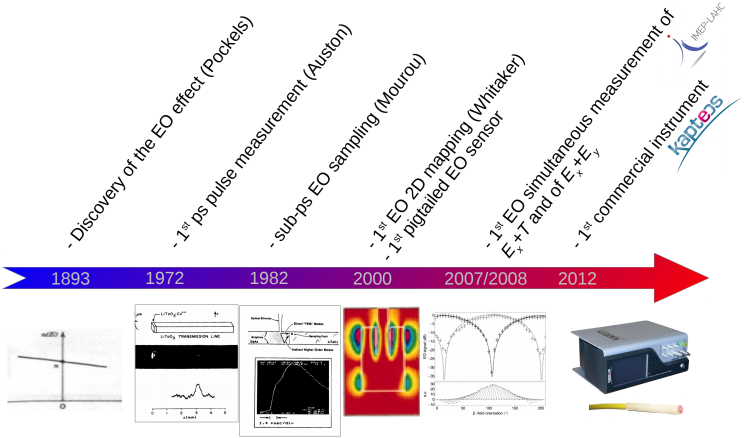


➥ EO sensors competitive exept concerning sensitivity

Outline

The electro-optic (EO) effect



The electro-optic (EO) effect

Pockels effect : **Linear** variation of the refractive index induced by the electric-field

$$\delta n = \vec{K}.\vec{E}$$

with $\vec{K}$ the sensitivity **vector*** depending on :

- the EO crystal
- the orientation of the optical wavevector/crystal

*Duvillaret *et al.*, JOSA B, 2002.

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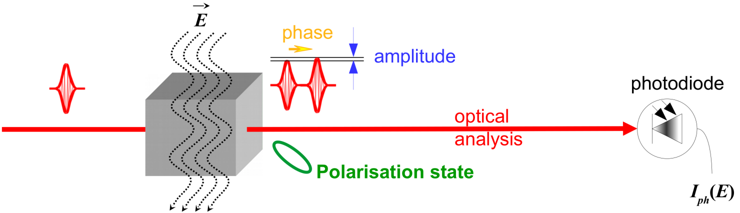

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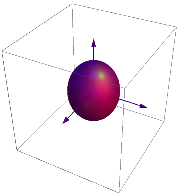
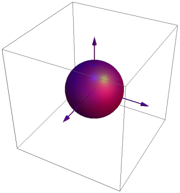
EO effect - crystals

Crystals and index ellipsoïd:

$$\vec{E} = \vec{0} \quad \Rightarrow \quad x^2\left(\frac{1}{n_x^2}\right) + y^2\left(\frac{1}{n_y^2}\right) + z^2\left(\frac{1}{n_z^2}\right) = 1$$

- The indices n_i are dependant on T
- $n_x = n_y = n_z = n_0$ for an isotropic



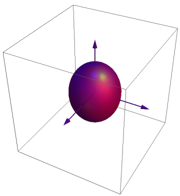


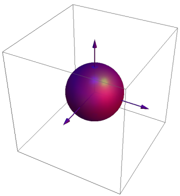
EO effect - crystals

Crystals and index ellipsoïd:

$$\vec{E} \neq \vec{0} \quad \Rightarrow \quad x^2\left(\frac{1}{n_x^2}+\delta_1\right) + y^2\left(\frac{1}{n_y^2}+\delta_2\right) + z^2\left(\frac{1}{n_z^2}+\delta_3\right) + yz\delta_4 + xz\delta_5 + xy\delta_6 = 1$$

- The variations δ_i are function of $\vec{E}(E_x, E_y, E_z)$
- $\delta_i =\lesssim 10^{-10} E_j$





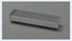
EO effect - crystals

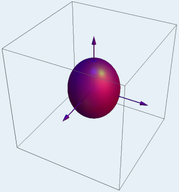
Crystals and index ellipsoïd:

$$\vec{E} \neq \vec{0} \quad \Rightarrow \quad x^2\left(\frac{1}{n_x^2}+\delta_1\right) + y^2\left(\frac{1}{n_y^2}+\delta_2\right) + z^2\left(\frac{1}{n_z^2}+\delta_3\right) + yz\delta_4 + xz\delta_5 + xy\delta_6 = 1$$

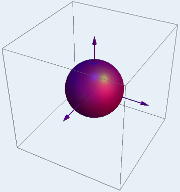
- The variations δ_i are function of $\vec{E}(E_x, E_y, E_z)$
- $\delta_i =\lesssim 10^{-10} E_j$

Index ellipsoïd and electric field

Anisotropic crystals 
($LiTaO_3$, $LiNbO_3$, ...)



Isotropic crystals 
(ZnTe, BSO, ...)



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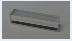
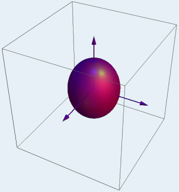
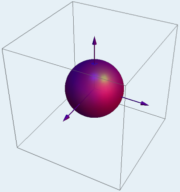




$\Rightarrow$ sensor E_j and T

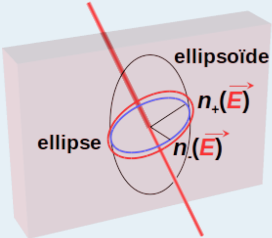
Isotropic crystals
(ZnTe, BSO, ...)



$\Rightarrow$ sensor $|\vec{E}_\perp|$ and $\gamma_{\vec{E}_\perp}$

The EO effect (2)

Index ellipse

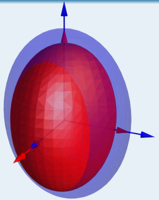


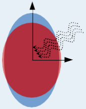
EO measurement via:

n_+ ou n_- ou

$\Delta n = n_+ - n_-$

Anisotropic crystal

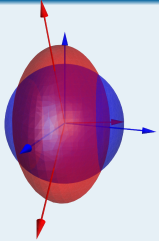


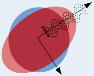


Δn_{aniso} is function of:

- Temp. T (quasistatic)
- 1 comp. of $\vec{E}$ (dynamique)

Isotropic crystal





Δn_{iso} is function of:

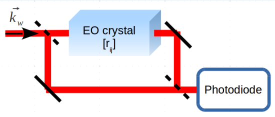
- E_x **AND** E_y (dynamic)

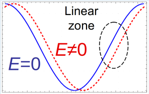
➡ Anisotropic EO crystal → measurement of E_x and T

➡ Isotropic EO crystal → measurement of E_x and E_y

EO modulation techniques

Phase modulation

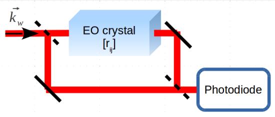


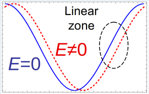


- √ Wellproven (modulator)
- √ Compatible with integrated optics
- X Control of the reference path
- X Sensitivity

EO modulation techniques

Phase modulation





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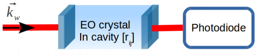
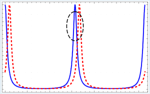
Amplitude modulation

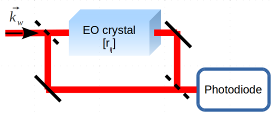


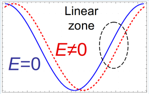


- √ sensor size
- √ Sensitivity
- X Sensor realization
- X Stability

EO modulation techniques

Phase modulation





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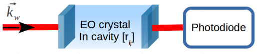

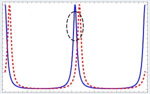

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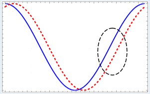
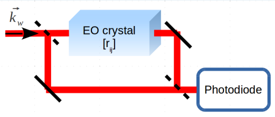
Polarization state modulation

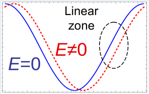


- √ External treatment
- √ "Simplicity" of the sensor
- X Sensitivity

EO modulation techniques

Phase modulation





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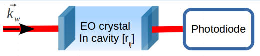
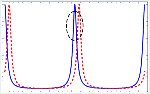
√ Compatible with integrated optics
X Control of the reference path
X Sensitivity

Amplitude modulation





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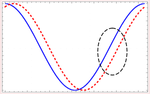

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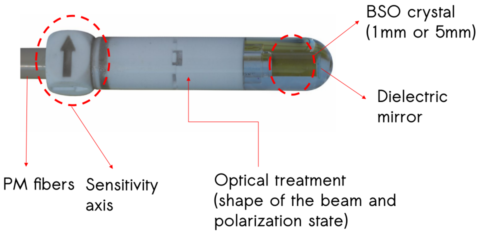
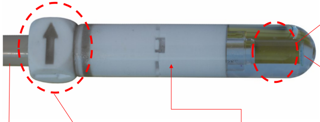
X Sensitivity

The EO probe



- Crystal size can be chosen depending on the application
- 2 probe sheaths: measurement in **air** or **water-based liquids**
- **Transverse** or **longitudinal** probe

The EO probe



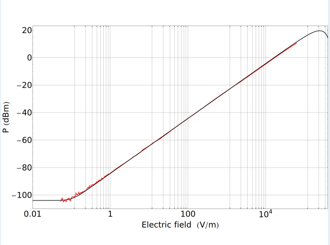
- Crystal size can be chosen depending on the application
- 2 probe sheaths: measurement in **air** or **water-based liquids**
- **Transverse** or **longitudinal** probe

➡ Dielectric sensor
➡ Millimeter sized
➡ Pigtailed probe ($\curvearrowright$ 100 m)
➡ Adaptative coating

EO probe performances (1)

Linearity

Response of the probe versus $|\vec{E}|$
$\longrightarrow$ depends on the EO coefficients, on the permittivity and on optoelectronic treatment



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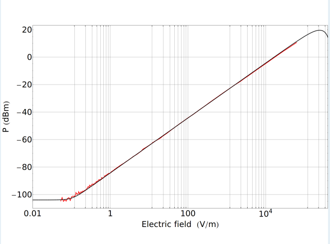
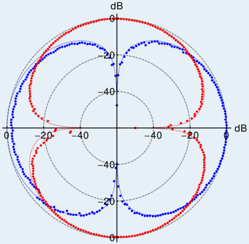


Vectorial selectivity

Response of the probe versus $\gamma_{\vec{E}}$
$\rightarrow$ EO intrinsicaly rejects the transverse component



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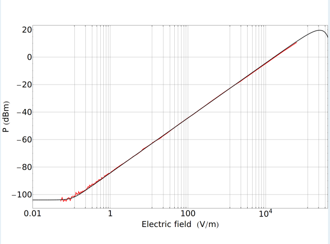

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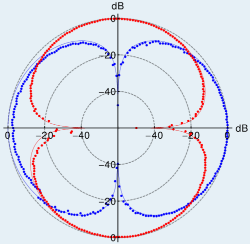


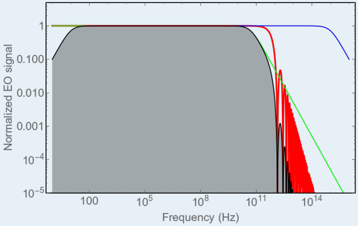
- Dynamics > 120 dB
- $|\vec{E}|_{min} < 1$ V.m^{-1}.Hz$^{-1/2}$
- Accuracy < 0.5 dB
- Selectivity > 65 dB

EO probe performances (2)

Bandwidth of the EO system

Frequency response depends on :

- Temporal response of the EO effect
- Frequency cut-off of the optoelectronic unit
- Photon lifetime within the crystal



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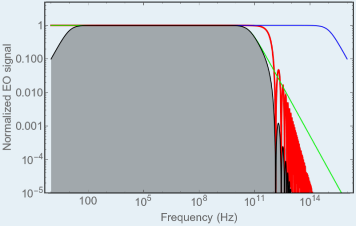

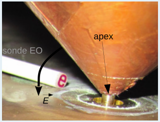

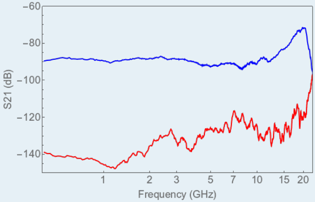

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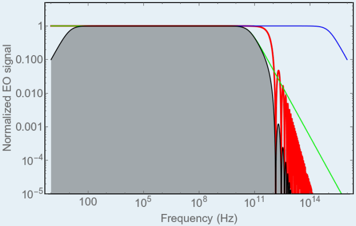

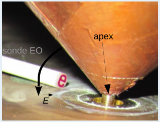

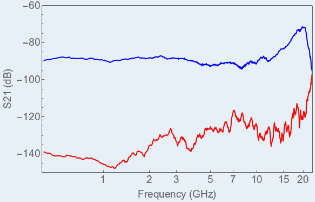

➡ Spectral response > 8 decades of frequency

Outline

Pulsed measurement

Comparative measurement of ns pulse:

EO probe  ↔ D-Dot  in a GTEM cell

G. Gaborit *et al.*, UWB-SP 10 Book, Chapter 6, Springer, 2013.

Pulsed measurement

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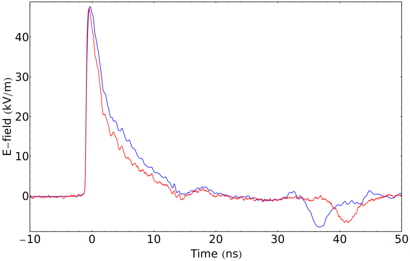

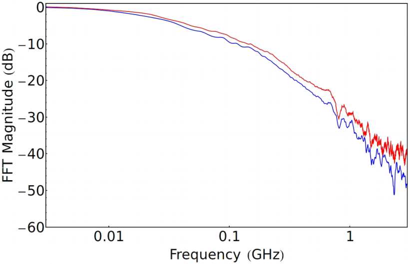

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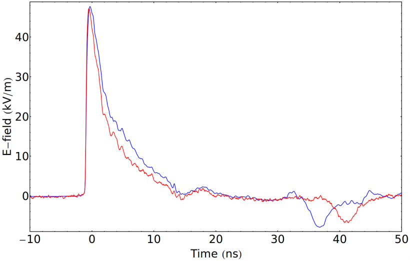
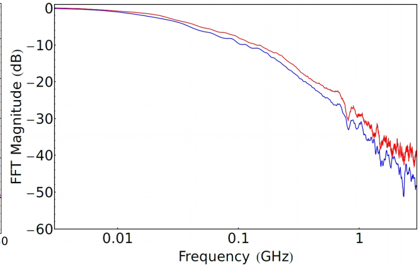


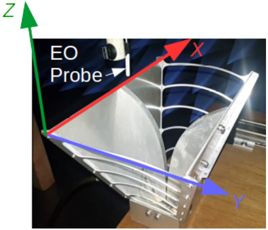


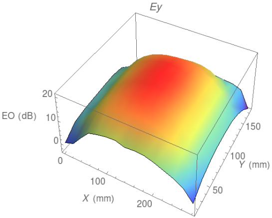
- EO measurement without any post-treatment
- Arbitrary positionning of the EO probe
- EO bandwidth → 20 GHz ≫ D-Dot bandwidth

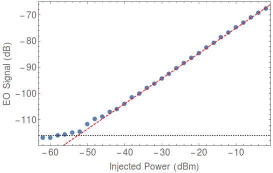
G. Gaborit *et al.*, UWB-SP 10 Book, Chapter 6, Springer, 2013.

Antenna

Vectorial mapping in the near field region:
→ Pattern in the vicinity of the antenna aperture (frequency domain-900 MHz) – **fundamental mode**







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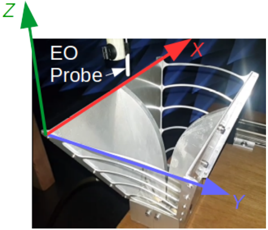
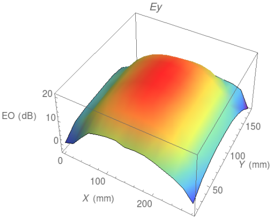
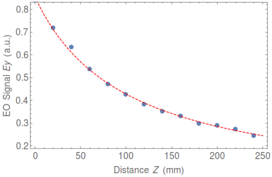
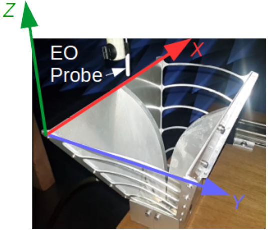


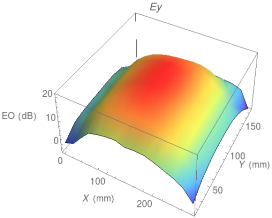


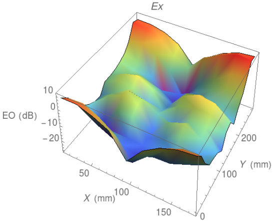


Antenna

Vectorial mapping in the near field region:
→ Pattern in the vicinity of the antenna aperture (frequency domain-900 MHz) – **cross polarization**

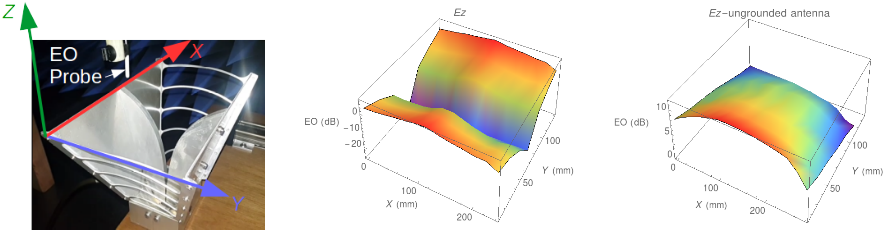






Antenna

Vectorial mapping in the near field region:
$\rightarrow$ Pattern in the vicinity of the antenna aperture (frequency domain-900 MHz) – **longitudinal field**



- No need of a "big" anechoic chamber
- Comprehensive reconstruction of the E-field **vector**

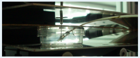
Simultaneous measurement of E/T

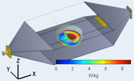
Bioelectromagnetism

Determination of the **Specific Absorption Rate**: $SAR = \frac{\sigma {E_{rms}}^2}{\rho} = C\frac{\partial T}{\partial t}$

Measurement conditions

- CW exposure 1.8 GHz
- *In situ* analysis of E et T





- Biological media: $\varepsilon_r = 77$

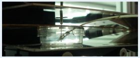
Simultaneous measurement of E/T

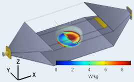
Bioelectromagnetism

Determination of the **Specific Absorption Rate**: $SAR = \frac{\sigma E_{rms}^2}{\rho} = C\frac{\partial T}{\partial t}$

Measurement conditions

- CW exposure 1.8 GHz
- *In situ* analysis of E et T





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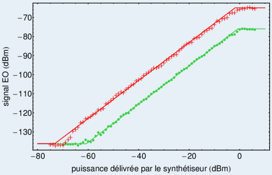
Response versus E

Response in the media and in air:



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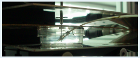

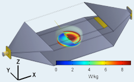

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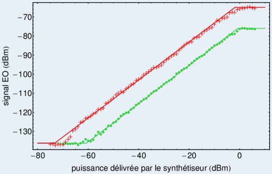
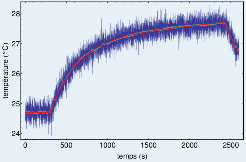


Temperature reponse

Comparative analysis:
EO probe ↔ Luxtron probe



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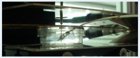

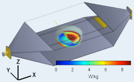

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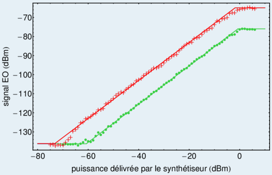

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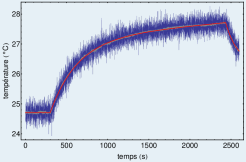
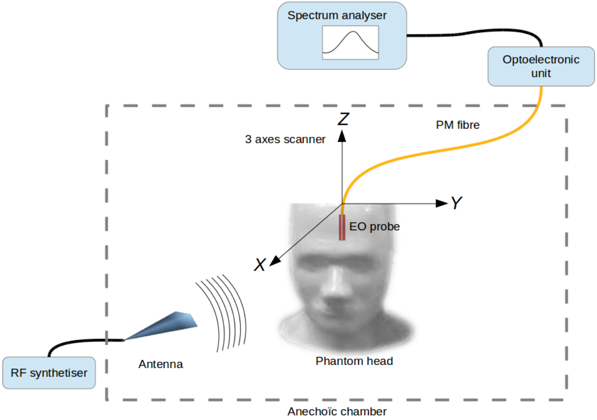


➡ $|\vec{E}|_{min,BIO} < 200$ mV.m^{-1}.Hz$^{-1/2}$ ➡ Resolution in $T < 30$ mK

Specific Absorbtion Rate

Determination of the SAR: 3D mapping inside a phantom head:



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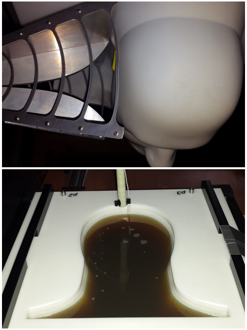
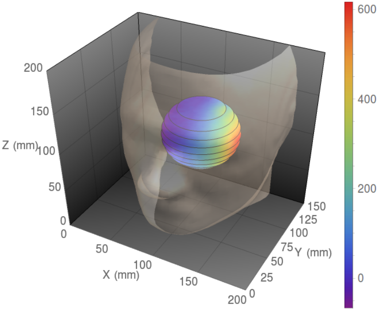


E-field within the phantom ($\varepsilon_r = 44.2 + i19.1$)



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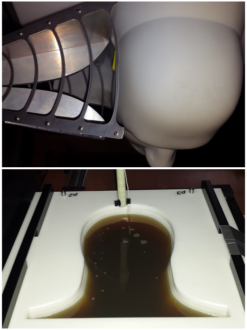

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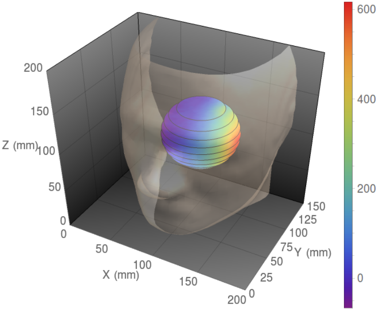
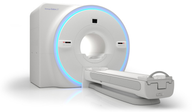


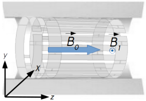
- Max. measured $SAR_{max} = 360$ W/kg
- Mesurement theshold as weak as 10 μW/kg

Magnetic Resonance Imaging

→ Very complex EM environment

- EM field:
  - DC B-field (3 T, 4.5 T and more),
  - **Pulsed RF B & E fields** (127 MHz, 200 MHz and more)
- Biological media under test:
  - $\mu_r \approx 1 \rightarrow$ no artefact on B gradient
  - heterogeneous in shape
  - heterogeneous in dielectric constant $\varepsilon_r = 20 \curvearrowright 60$ and $\sigma = 0.1 \curvearrowright 1$ S/m





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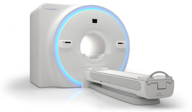

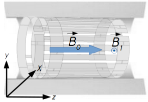

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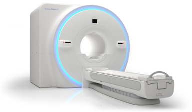

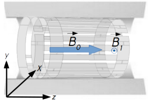

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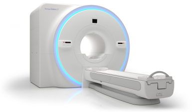

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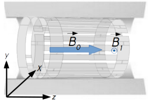
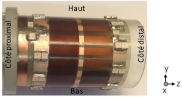
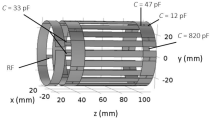


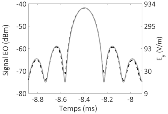
➡Measurement of the E-field to analyse the **radiation pattern of the birdcage** & the **exposure of the biological media (SAR)**

MR images and SAR

→ Mapping of the rms field in a pre-clinical 4.7 T MRI*







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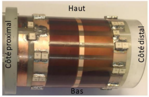

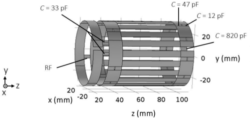

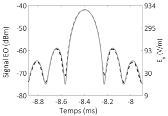

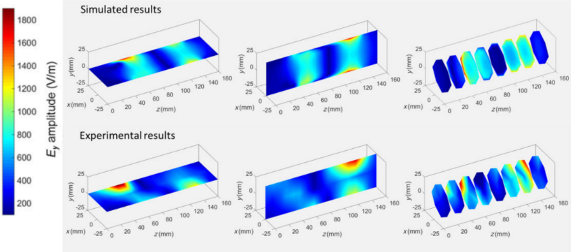

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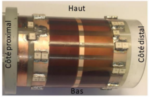
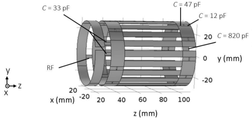
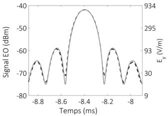
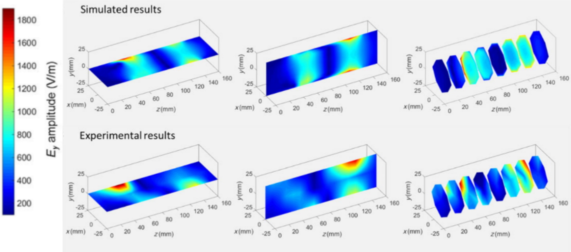




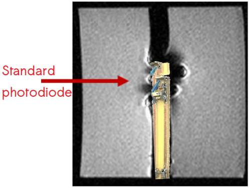


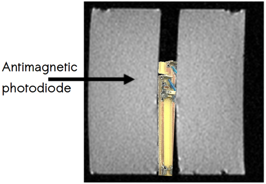


➡Very good agreement between measurements and simulations

MR images and SAR

MR image using a patch antenna with optical decoupling:
→ local modification of static B field
→ **Strong image distortion induced by an ultra small non antimagnetic component!**





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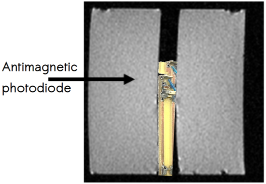
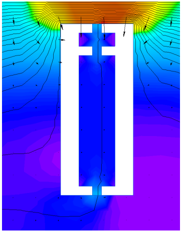


MR image using a patch antenna with optical decoupling:
→ local modification of RF E field
→ **Strong modification of the local SAR**



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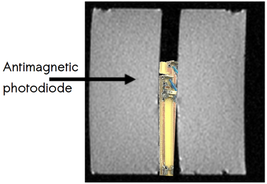

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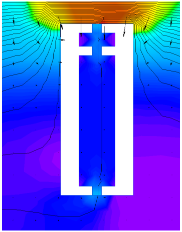
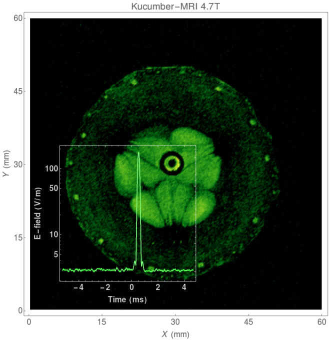


➡Devices, components, connections, and cables have to be qualified for a use in MRI system

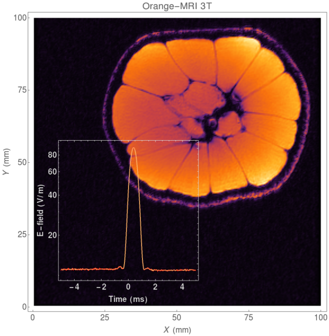
MR images and SAR

E-field measurement inside biological media

→ Fully **artifact-free** images (RBW = 100 kHz)



Lab MRI 200 MHZ (birdcage ant., flash seq.)



Clinincal MRI 127 MHz (wrist ant., gradient echo seq.)

MR images and SAR

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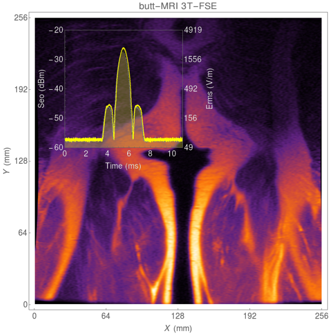

In vivo analysis Clinincal MRI 127 MHz (pelvis ant., gradient echo seq.)

MR images and SAR

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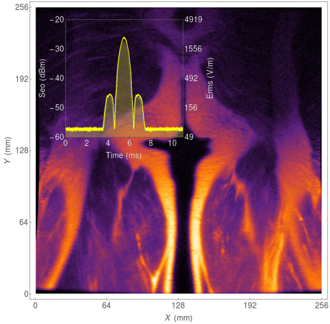
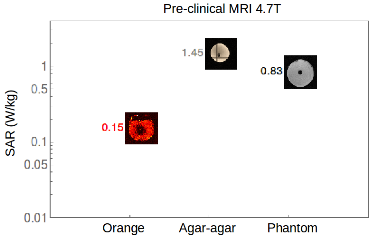


In vivo analysis Clinincal MRI 127 MHz (pelvis ant., gradient echo seq.)

➡Image modified only due to the insertion of the probe (no distorsion of the field)

MR images and SAR

SAR assessment



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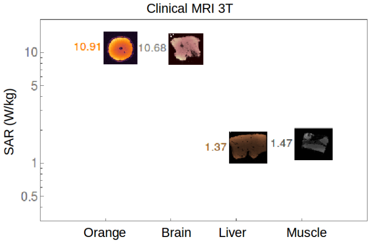

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MR images and SAR

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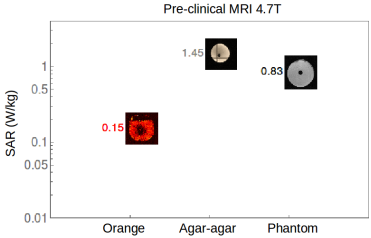

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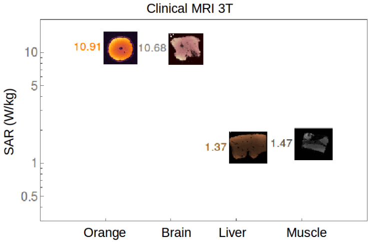


Clinincal MRI 127 MHz (wrist ant.)

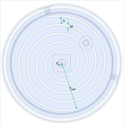
➡*In-situ* & real time monitoring of the SAR
➡The exposure depends dramatically on **the complex permittivity** AND on **the shape** of the imaged media

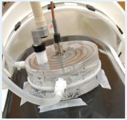
Hyperthermia in MRI

→ **Applying RF field** (Sine 115 MHz) to localy increase the temperature and hense, **improving the efficiency of chemotherapy**

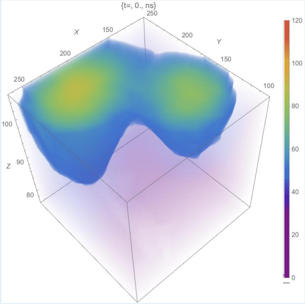
Spiral antenna (⌀15 cm)

- Placed **outside the body** to heat tumor **inside the body** (44 °C)
- Feeding source CW: 100 W, 115 MHz
- $\lambda_{air} \approx 2.5$ m, $\lambda_{body} \approx 30$ cm



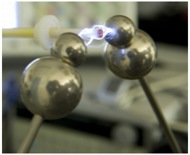


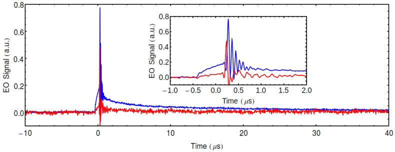
4D mapping of the *in-situ* rms E-field deduced from E_i, φ_i



Intense electric field

Single shot measurement of E_x and E_y within a discharge:





G. Gaborit *et al.*, IEEE Plasm. Sci., 2014.

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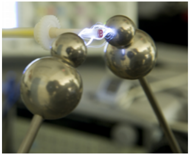
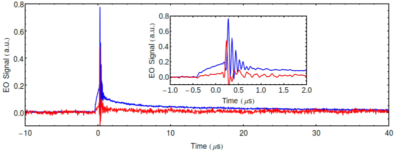
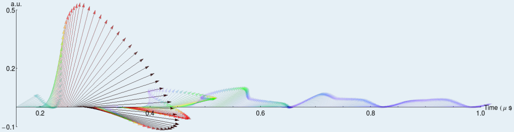




Plasma oscillation



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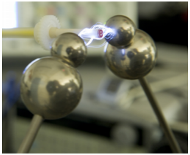
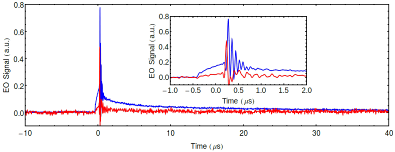
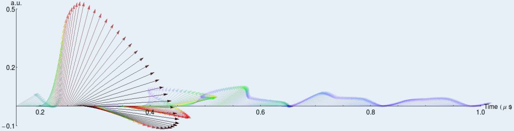




Plasma oscillation

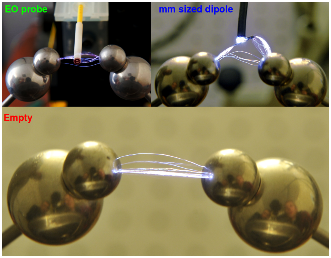


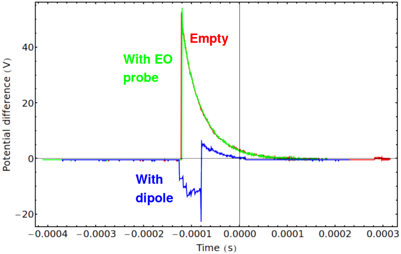
- E-Field up to more than 3 MV/m
- Alternate characterization impossible

G. Gaborit *et al.*, IEEE Plasm. Sci., 2014.

Intense electric field

Disturbance on the potential difference inducing the discharge (measured with a home-made resistive divider):





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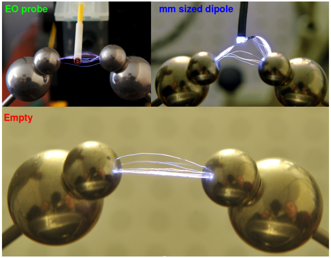

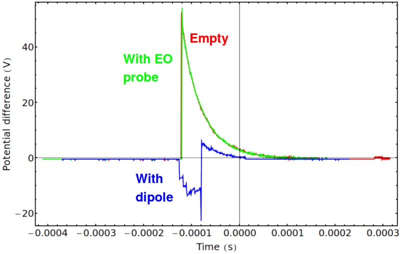

- Very weak induced perturbation on the field
- No disturbance on the field applicator

G. Gaborit *et al.*, IEEE Plasm. Sci., 2014.

Plasmas

- 4^{th} state of matter
- constitute more than 99.9 % of the universe (both in volume and mass)
- used in a lot of applications: surface treatment of liquid/solid, medicine, agriculture, combustion, propulsion, nanofrabrication . . .

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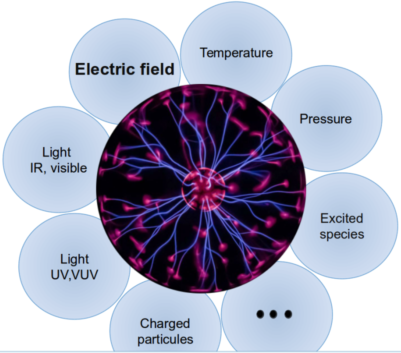
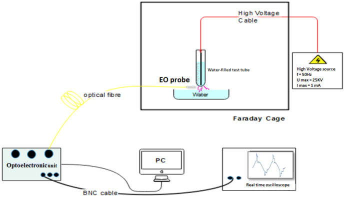


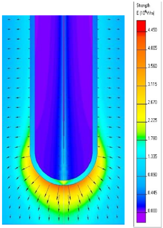
Plasma analysis

Dielectric Barrier Discharges (DBD):



- Voltage source: 50 Hz, [0-25] kV, 1 mA

- Implemention fully suitable for:
  - DBD (in the [15-25] kV range)
  - E-field measurement with the EO probe



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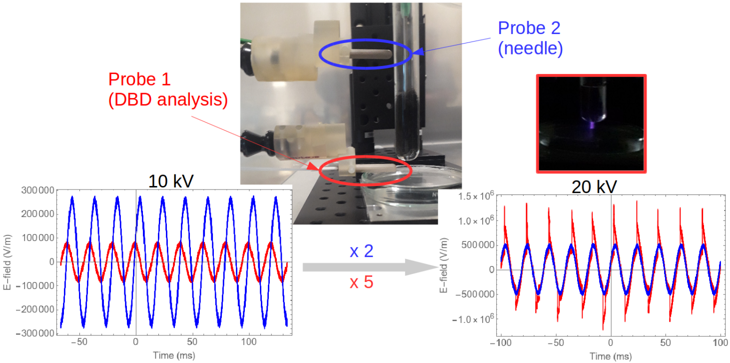

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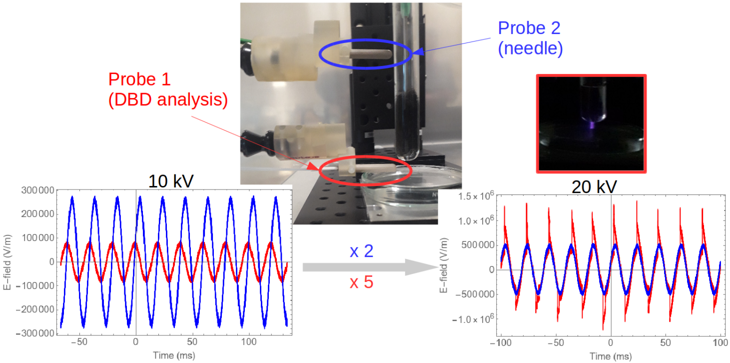
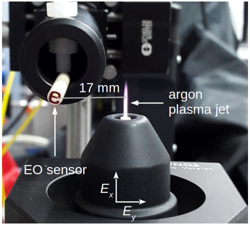
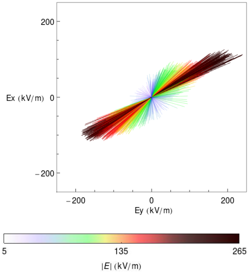


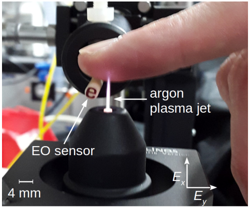
- Non-linearity between voltage and field
- Phase shift of 90° induced by the charged species

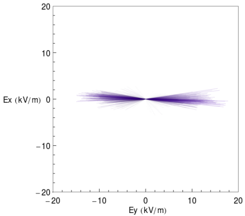
Plasma analysis

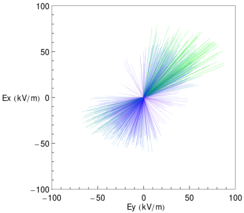
Ar plasmajet and target: The Ar Plasma jet is fed by a voltage signal at 1 MHz, *i.e* the **single shot vectorial field pattern** is obtained in 1 μs











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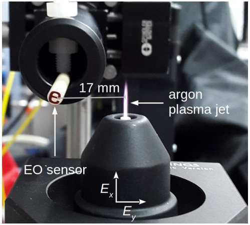
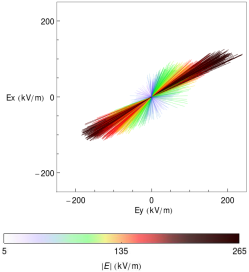
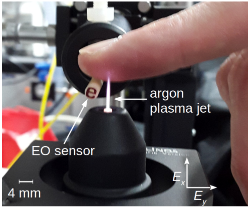
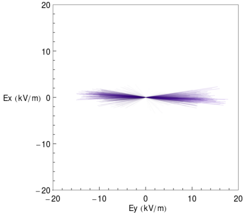
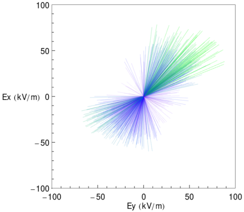






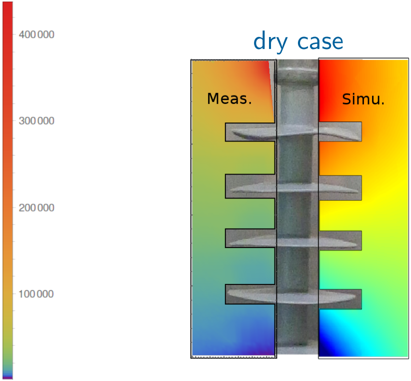


➡ The **plasma behaviour** is be affected by the target (have to be taken into account)



High Voltage and energy

→ 25kV composite insulator: Radial E field mapping at 50 Hz (meas. in time domain, dynamic range > 50 dB)



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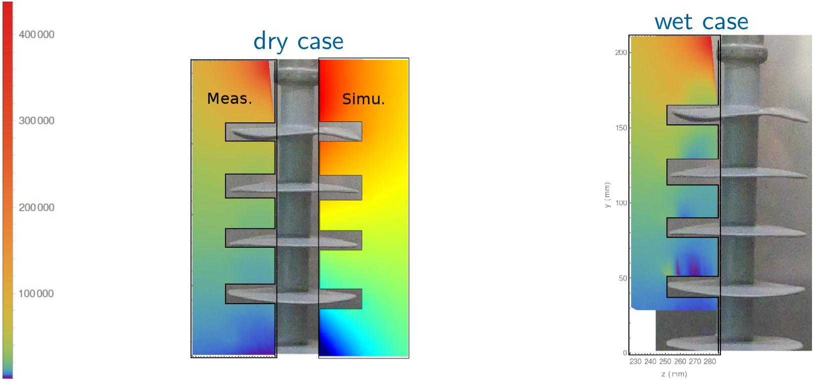

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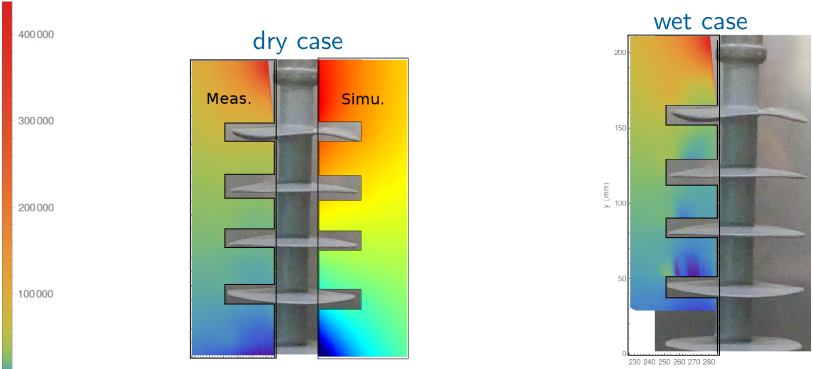
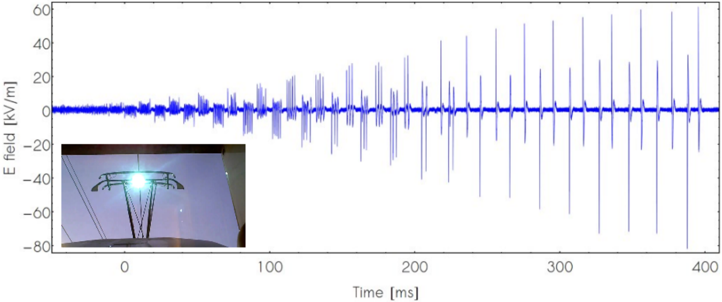


- E-field analysis instead of visual/electrical inspection
- Other similar cases: pollution, salt fog, icing, bird poop, . . .

High Voltage and energy

EM perturbations on train busbar:
Pantograph lowering → Electric arcs



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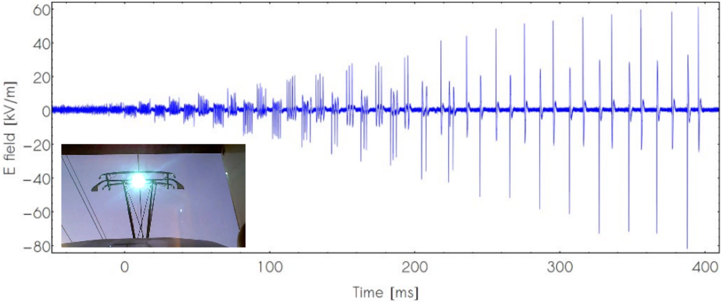
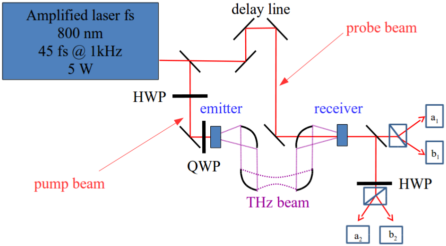


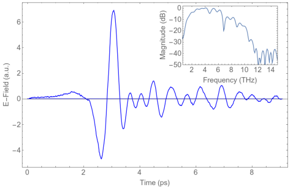
- Few hundreds discharges (only a few tens were expected)
- Increasing E-field vs time
- Early ageing of pentographs and transformers

Reaching TeraHertz Frequencies

Working in the equivalent time domain (repetitive pulses only-no jittered signal):

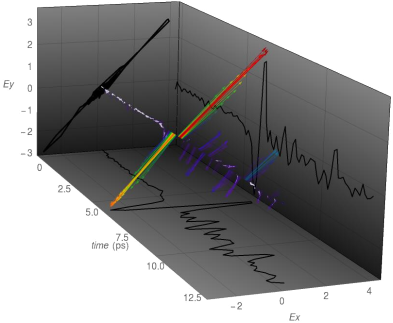
emitter/receiver=cubic crystal (ZnTe <111>)



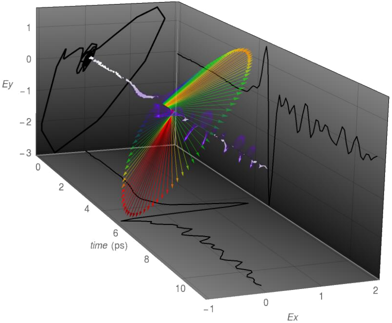


Reaching TeraHertz Frequencies

Linear polarization state of the THz beam generated with a **linearly polarized** laser beam



Elliptical polarization state of the THz beam generated with a **circularly polarized** laser beam



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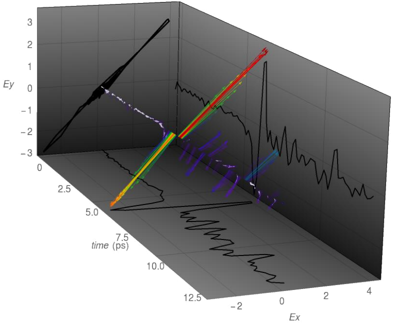

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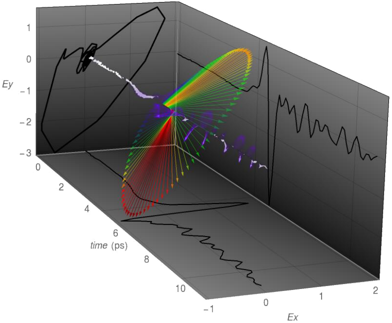

- Measurement of ps pulses
- vectorial measurement up to 10 THz

Outline

Conclusion

Performances of the EO technique:

- ✔ Fully dielectric sensor
- ✔ Millimeter sized
- ✔ Spatial resolution better than 1 mm^3
- ✔ Minimum detectable field lower than 100 $mV.m^{-1}.Hz^{-1/2}$
- ✔ Achievable dynamics of more than 120 dB
- ✔ Frequency bandwidth up to 100 GHz in real time (40 GHz for commercial product)
- ✔ Vectorial selectivity better than 50 dB
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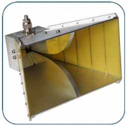
- ✔ Antenna
- ✔ MRI
- ✔ Plasma
- ✔ Energy
- ✔ SAR
- ✔ EMC



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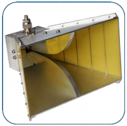

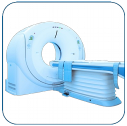

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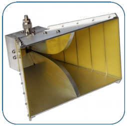
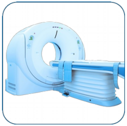
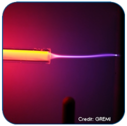

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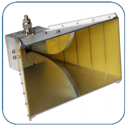
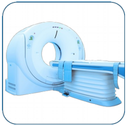
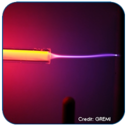

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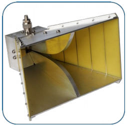
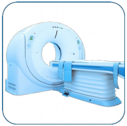
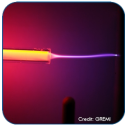


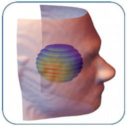

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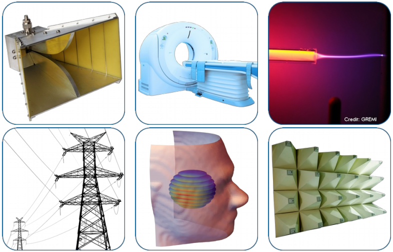
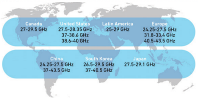


Outlooks and challenges

- New generation of mobile telecommunications : 5G
- Aerospace (characterization of Tx antenna)
- Interaction between pulsed laser and plasmas



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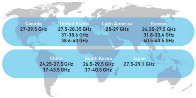

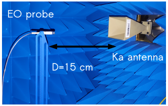

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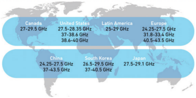

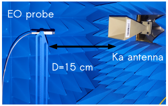

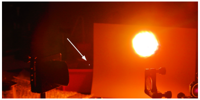

THANK YOU FOR YOUR ATTENTION !!!

Questions/Discussion???