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AVANTAGES ET LIMITATIONS A L'INTEGRATION DES FIBRES OPTIQUES ET CAPTEURS A FIBRES OPTIQUES DANS LES ENVIRONNEMENTS RADIATIFS

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VERRES IRRADIES
Atelier du GDR Verres & USTV
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http://nice2015.sciencesconf.org

BASICS OF RADIATION EFFECTS ON OPTICAL FIBERS

Silica-based optical fibers present **several advantages** compared to copper cables for use in nuclear environments

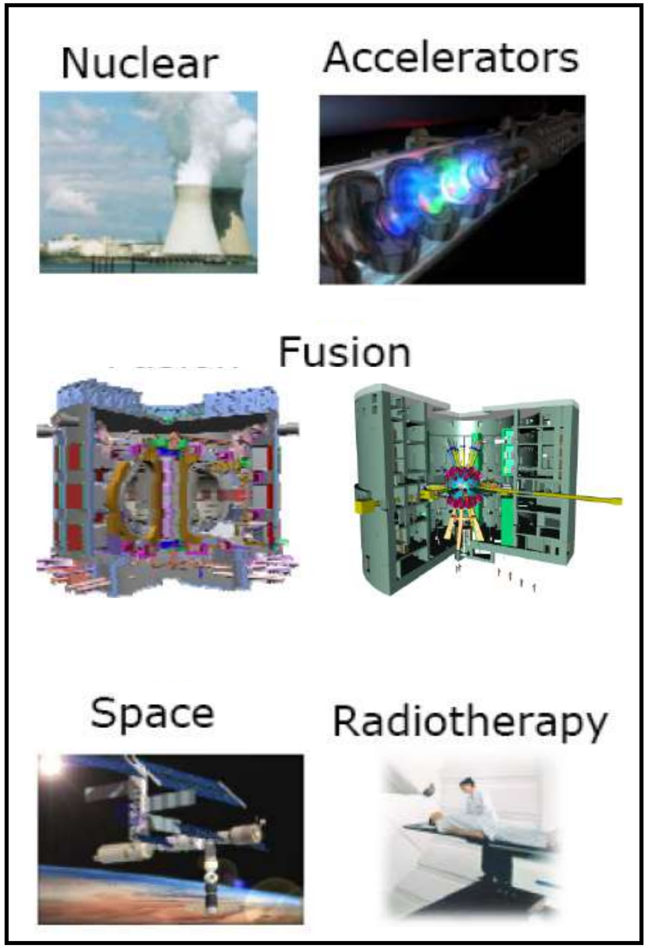
1. **Electromagnetic immunity**
   Copper cables present parasitic transient currents

2. **High bandwidth/ multiplexing capability**
   Huge amount of data can be transferred and multiplexed

3. **Low attenuation**
   Typical linear attenuation of 0.2 dB/km for fiber optic versus 20 dB/km for copper cables

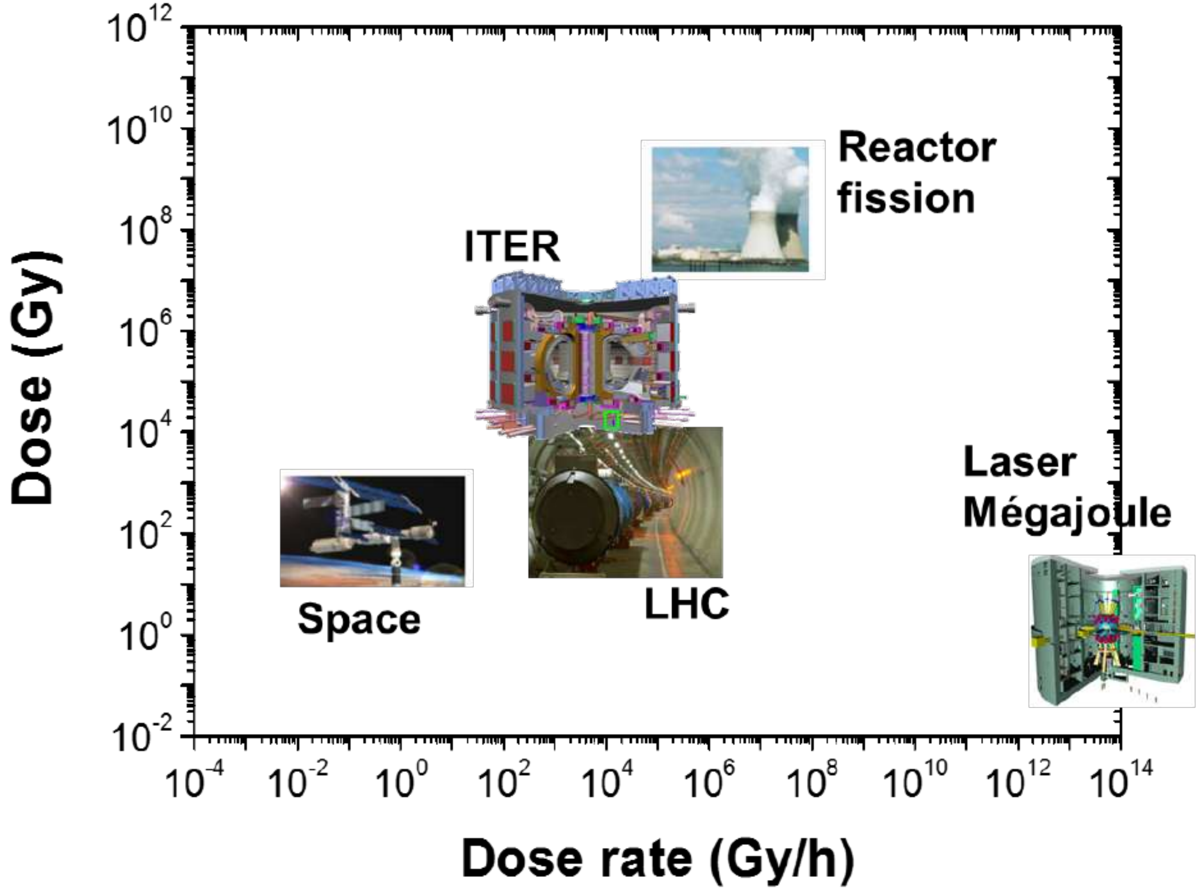
4. **Low weight and volume**
   Allows to reduce the levels of activated materials

5. **High temperature resistance**
   Can resist to temperatures higher than 300°C with appropriate coatings



Courtesy B. Brichard (SCK-CEN)

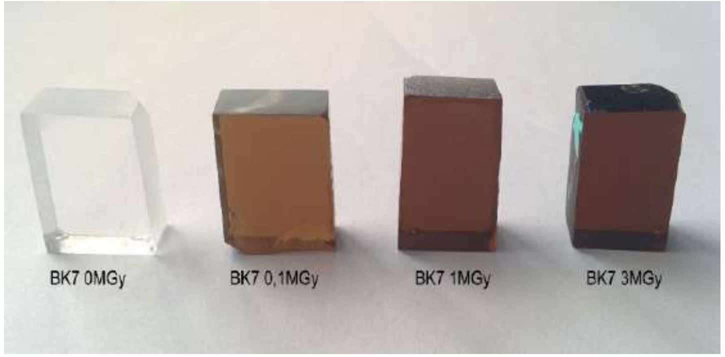
Silica-based optical fibers present **several advantages** compared to copper cables for use in nuclear environments



→ However, the fiber optic properties, like those of copper cables, are also affected by radiations

Three degradation mechanisms at macroscopic scale have been identified under irradiation:

1. **Radiation-Induced Attenuation (RIA)**



2. **Radiation-Induced Emission (RIE)**

Irr. OFF ***Irr. ON***

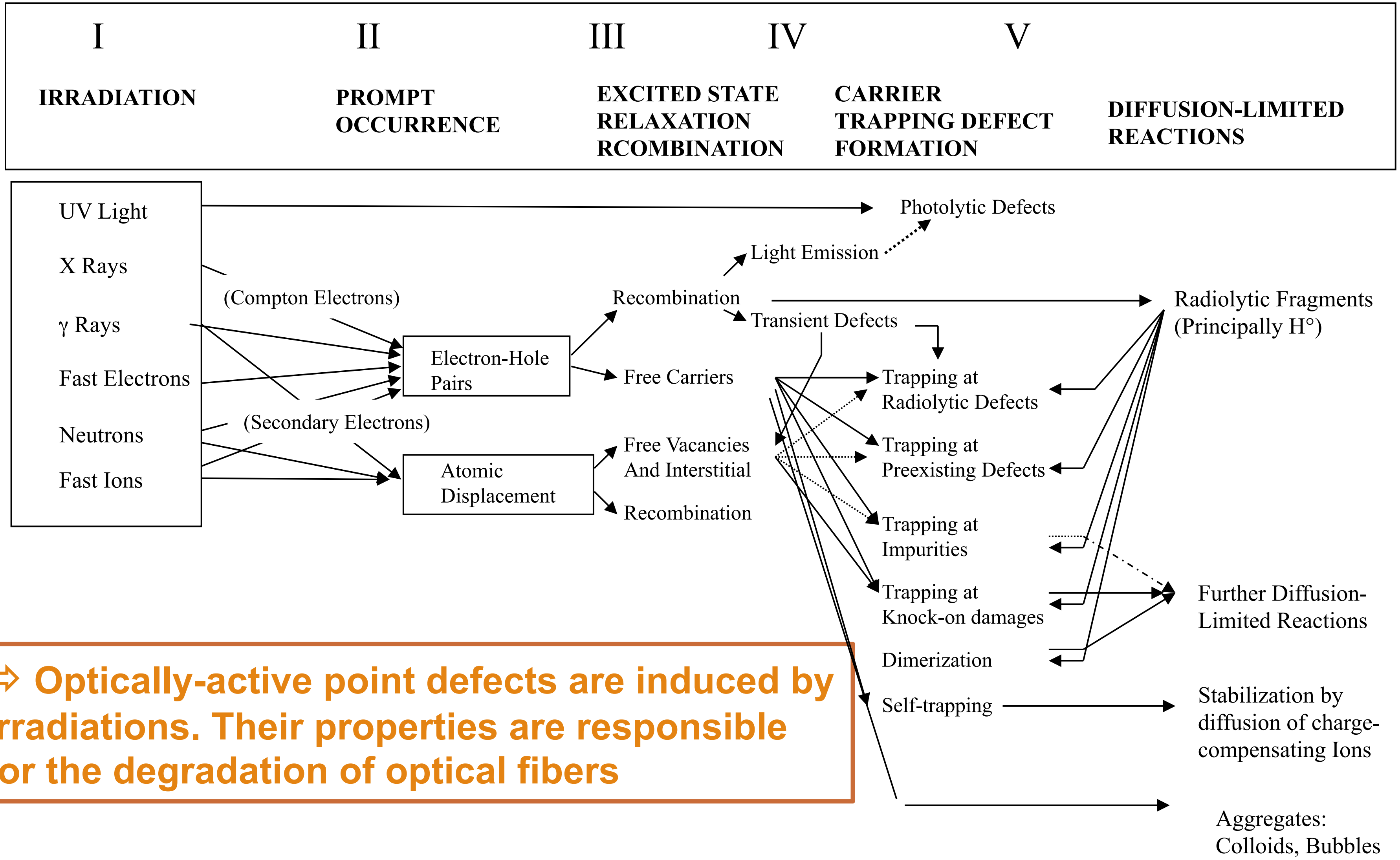
3. **Compaction**

@ 1MGy ($\Delta n = -7.4\times10^{-3}$)

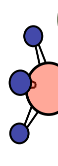
- **The relative influence of these 3 mechanisms depends on the <u>radiation environment</u> associated with the fiber-based system and on the <u>targeted application</u> (fiber sensors)**

Radiation-induced mechanisms occurring at the **microscopic scale** in *a*-SiO_2 have been identified

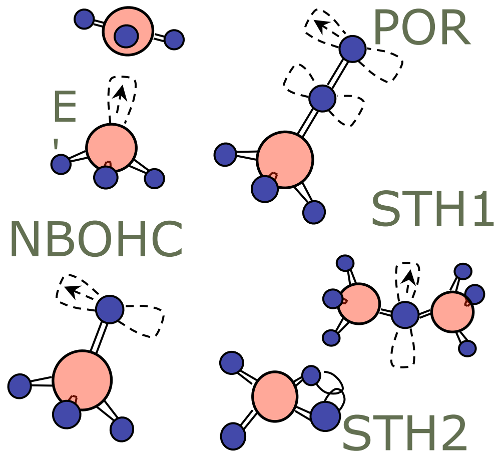
Griscom D.L. SPIE vol. 541, 1985

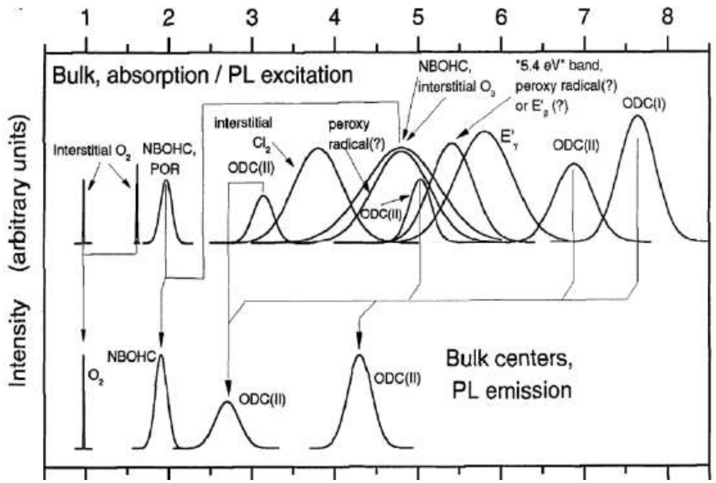


⇨ Optically-active point defects are induced by irradiations. Their properties are responsible for the degradation of optical fibers

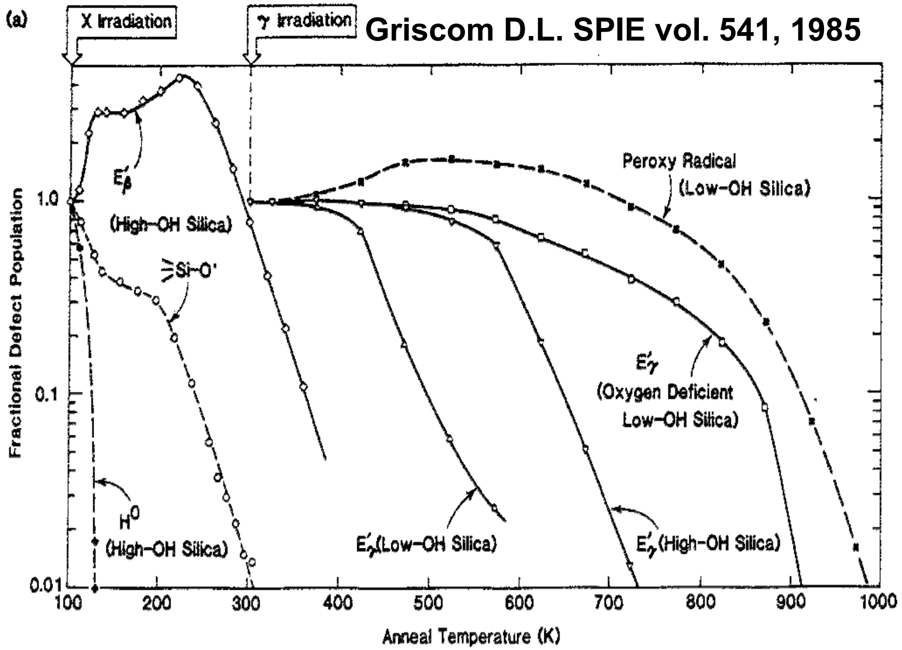


Optical and energy properties of these point defects explain the complexity of the fiber radiation-response





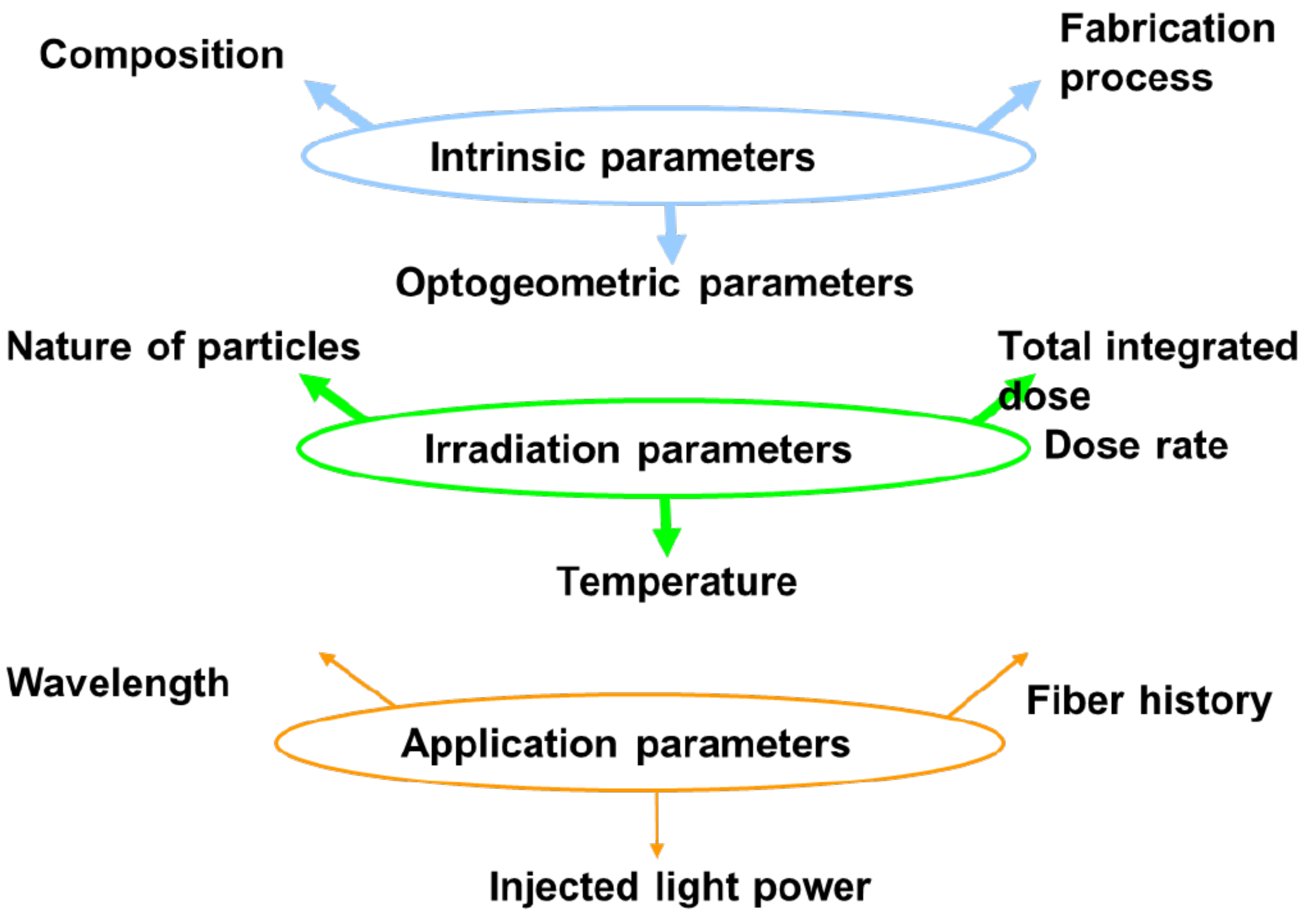
L. Skuja; NATO Book Chapter, 2000



Griscom D.L. SPIE vol. 541, 1985

- ➢ Each parameter affecting the stability, generation efficiency or optical properties of these point defects will affect the fiber radiation response.

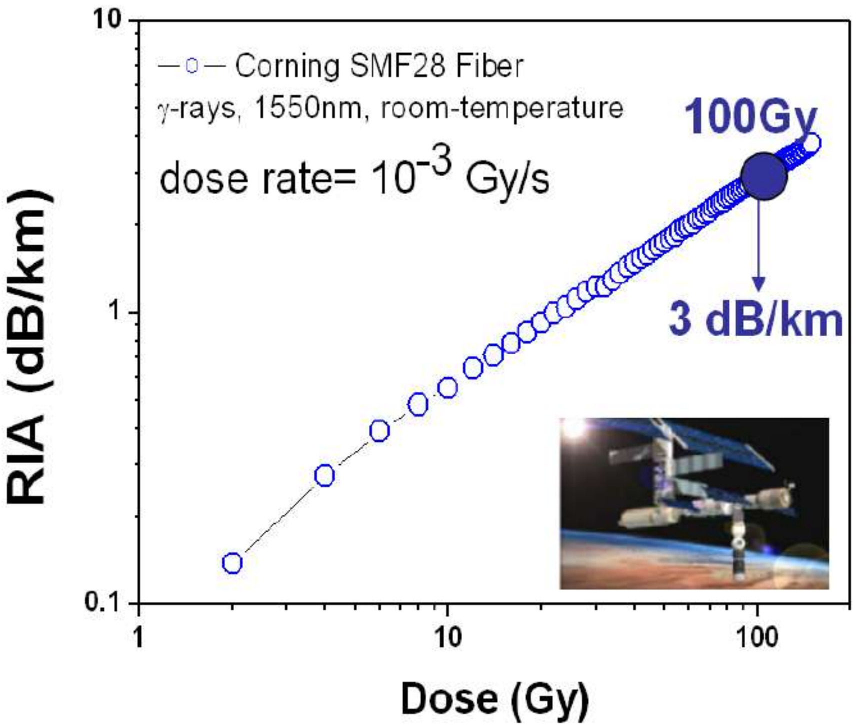
Numerous parameters, intrinsic or extrinsic to the fiber influence its radiation response

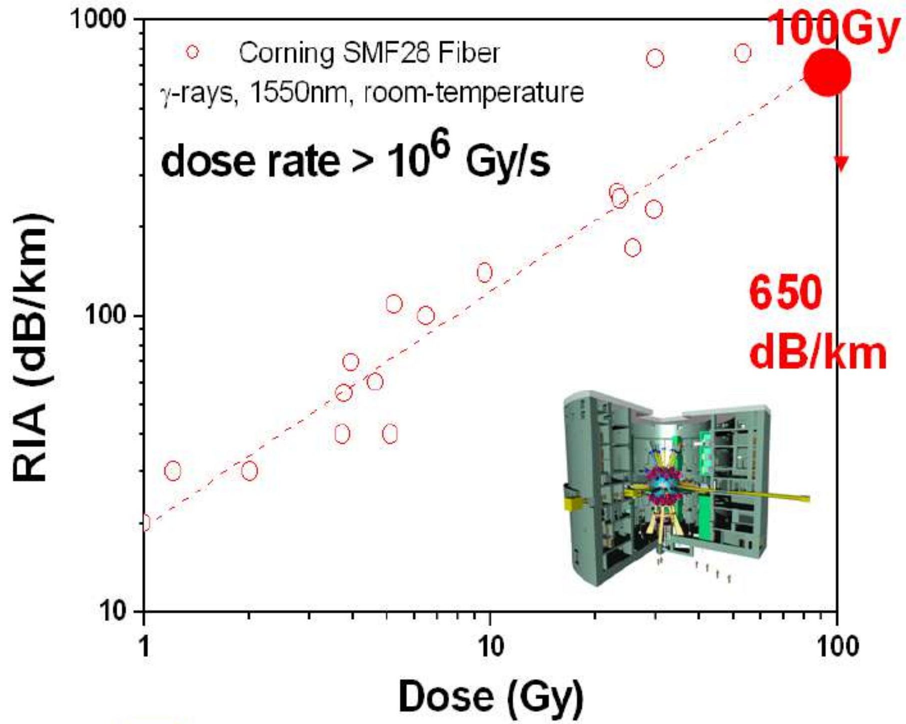


- These parameters affect the radiation-induced attenuation (RIA) levels that mainly define the **fiber vulnerability** for data transport

Fiber vulnerability: RIA growth kinetic depends on the harsh environment: *dose, dose rate, T, irradiation duration,…*

⇨**Vulnerability of a given fiber strongly depends on the harsh environment associated with the application**

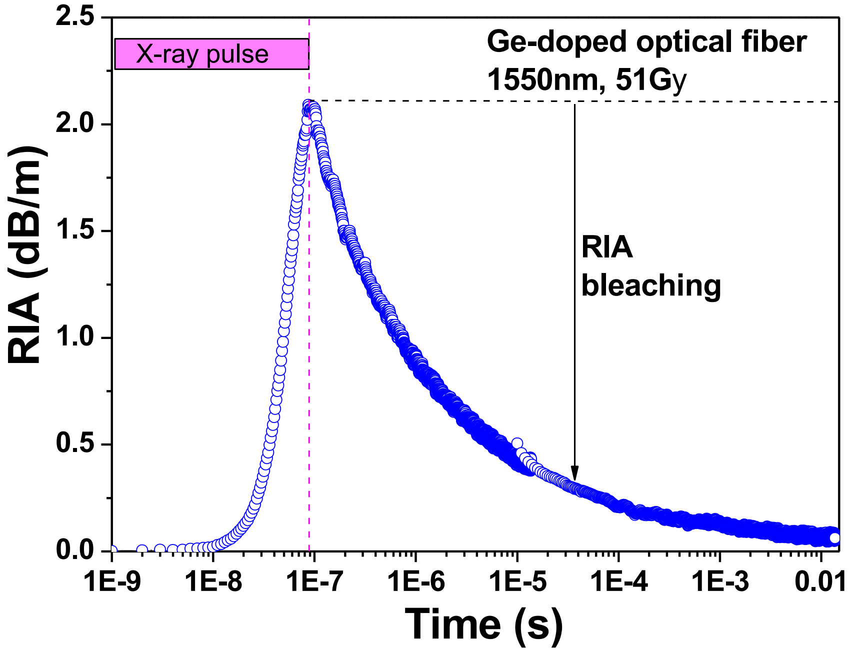


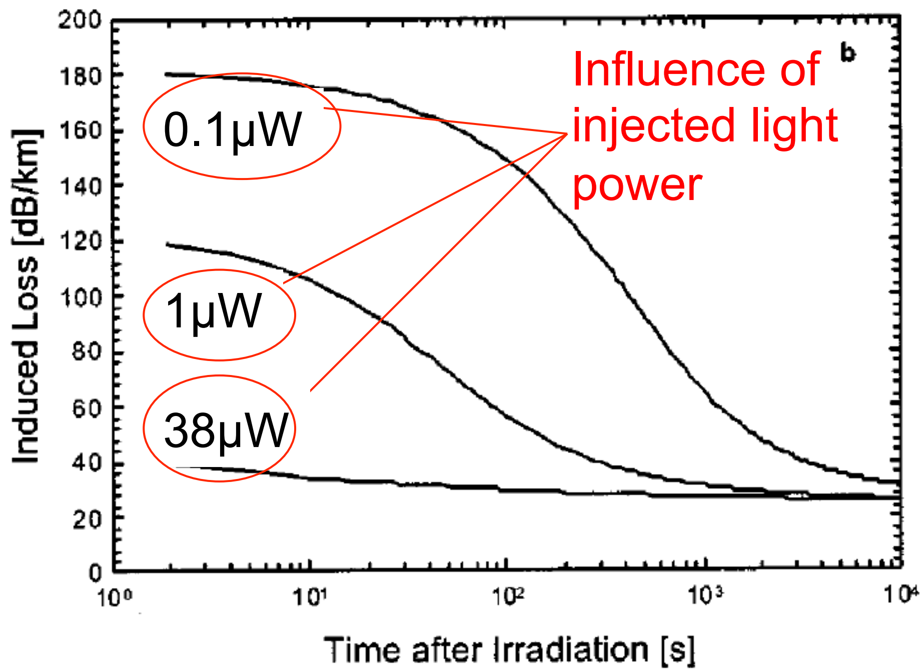


$$RIA = f(t, D, \dot{D}, T)$$

Fiber vulnerability: RIA decay kinetic after irradiation ⇨ drive the fiber recovery between successive irradiations

- Majority of defects is unstable at the temperature of experiments ⇨ the **RIA decreases with time after irradiation**
- The bleaching kinetics and efficiency depend on many parameters: *temperature, wavelength and power levels of the injected signal, …*

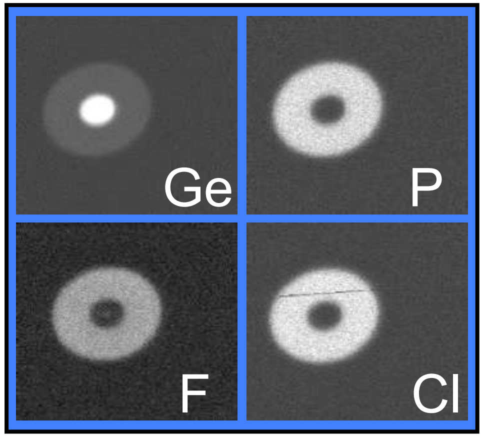




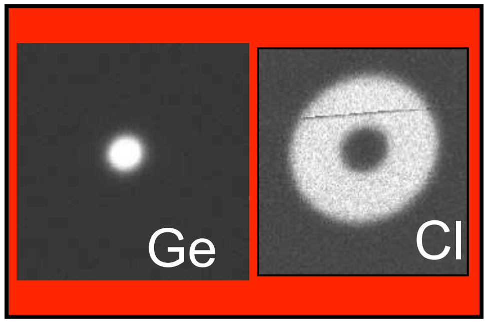
H. Henschel et al., *IEEE TNS* **49**, 2002.

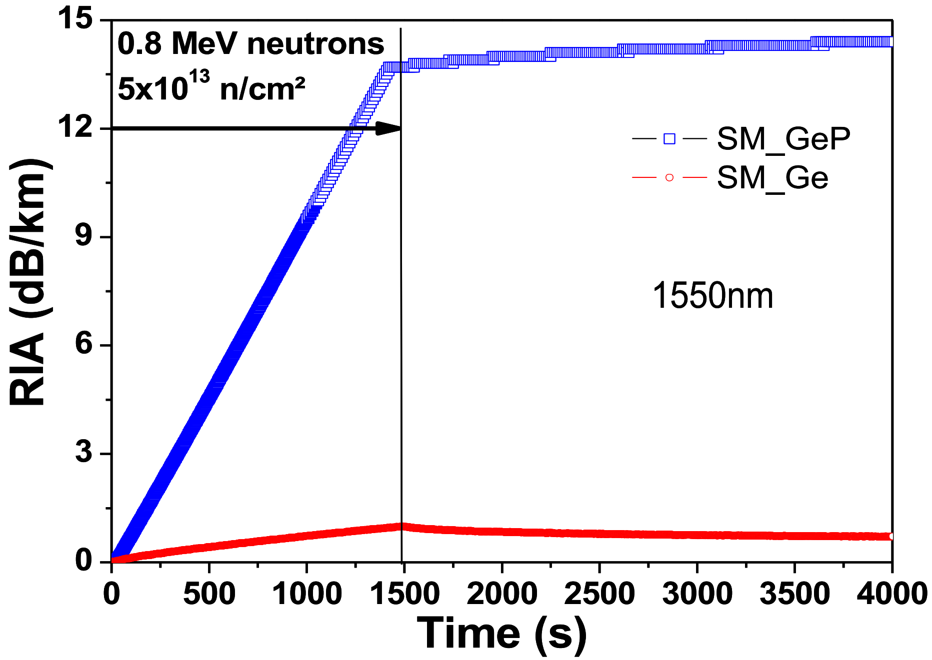
Fiber sensitivity strongly depends on the fiber composition: core & cladding dopants, stœchiometry, impurities, …

- A **slight** change in fiber composition **strongly** changes the nature, concentration and stability of induced defects



2 Telecom SMF with the same optical characteristics but different cladding compositions





IDENTIFICATION OF POINT DEFECTS IN SILICA-BASED MATRIX: EXPERIMENTAL TOOLS

The association of *in situ* and *post mortem* experiments is necessary to identify radiation-induced point defects and their generation mechanisms

***In situ* Experiments:**

Characterization of both unstable and stable point defects

***Post mortem* Experiments:**

Characterization of the stable point defects

Irradiations facilities

- Pulsed X-rays
- 1.2 MeV gamma-rays
- 14 MeV and 0.8MeV neutrons
- 10 keV X-ray experiments
- Protons, Laser exposures

Treatments

- Hydrogenation
- Temperature

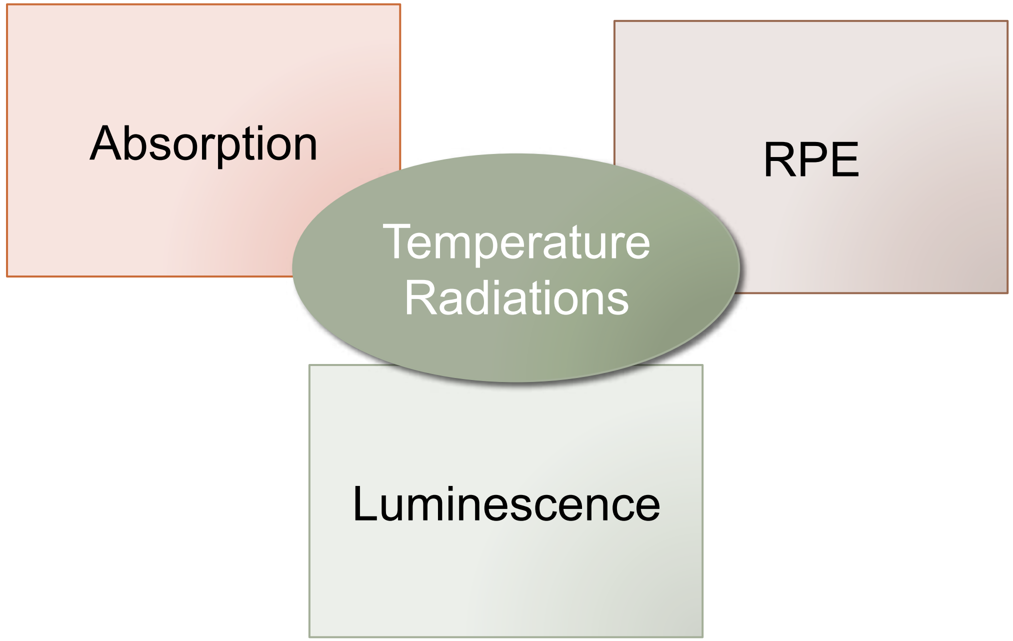
Spectroscopic techniques

- ✓ Absorption (spatially-resolved)
- ✓ Luminescence (spatially-resolved)
- ✓ RPE
- ✓ Raman
- ✓ Thermoluminescence
- ✓ VUV absorption
- ✓ Cathololuminescence

METHODOLOGY

- The most efficient way to identify a point defects and its associated optical properties **is to combine different spectroscopic techniques**

- In fact, all techniques present some limitations (online?, spatially-resolved?, paramagnetic?) and such assignments remain very difficult

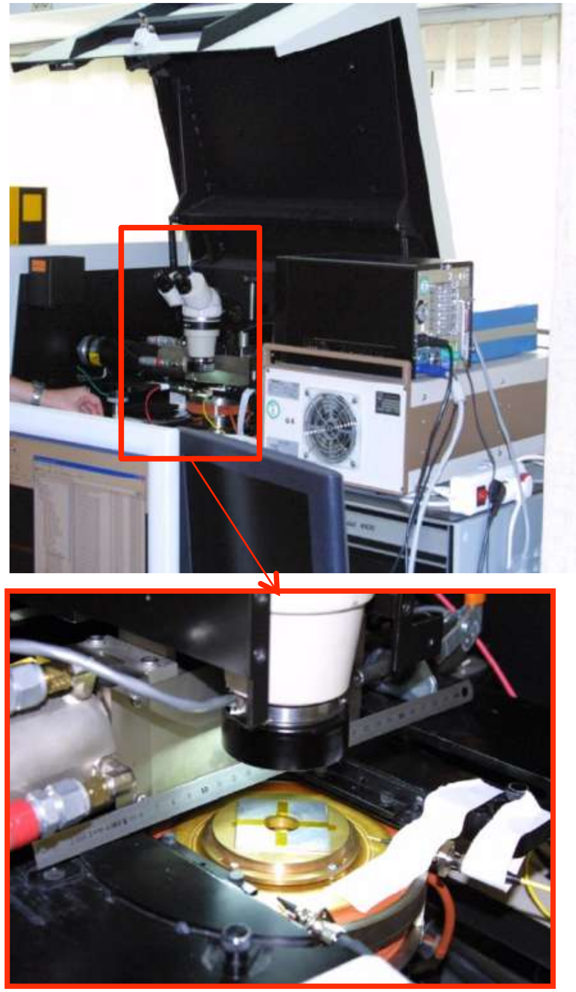


On the natures of radiation-induced point defects in GeO_2-SiO_2 glasses: reevaluation of a 26-year-old ESR and optical data set

David L. Griscom,[1,2,*]

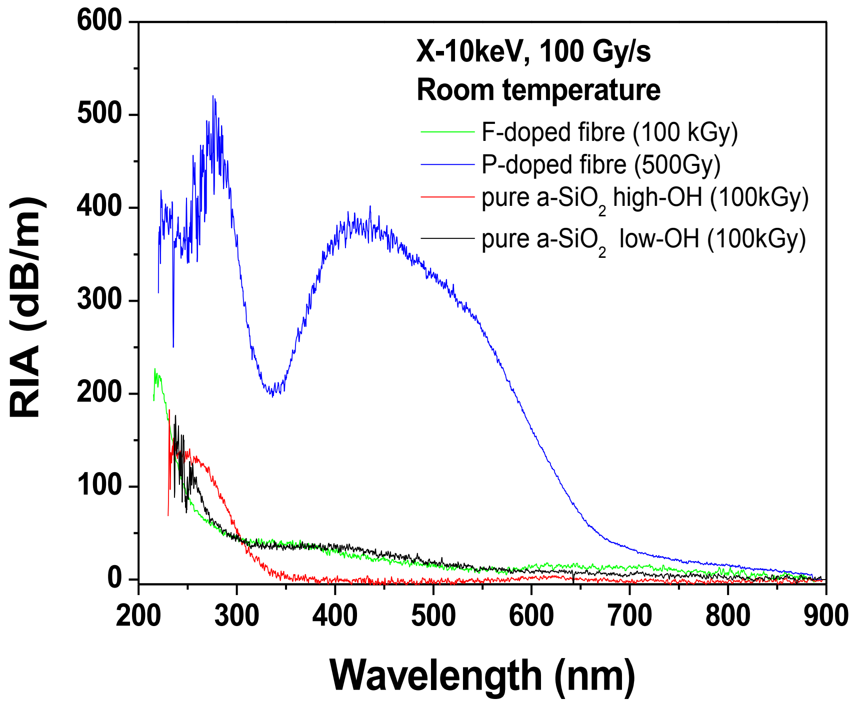
DIFFERENT TECHNIQUES: ABSORPTION MEASUREMENTS

Study of radiation-effects on FOs in the UV range is possible with X-ray machines (ARACOR, PROBIX at CEA : MOPERIX at LabHC)



- **ARACOR Machine**
  - ✓ Dose rate up to 50Gy/s, T from -50°C to +150°C
  - ✓ Highly-focused beam (max 3 cm)

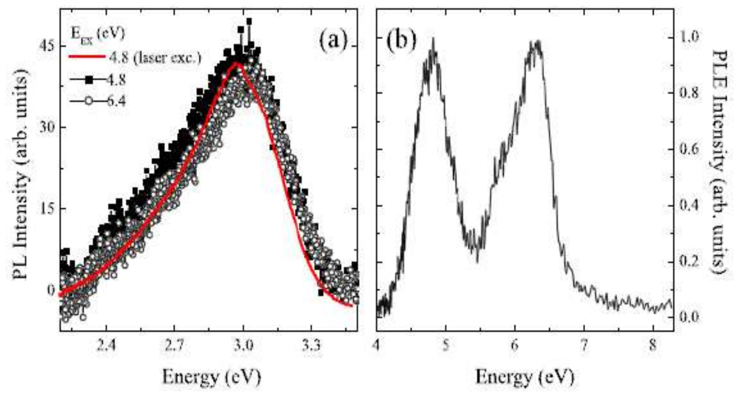
- **The test bench has been**
  - ✓ optimized to study radiation effects on pure-silica core, F and Ge-doped FOs in the UV
  - ✓ used to irradiate FOs & glasses for post mortem analyses

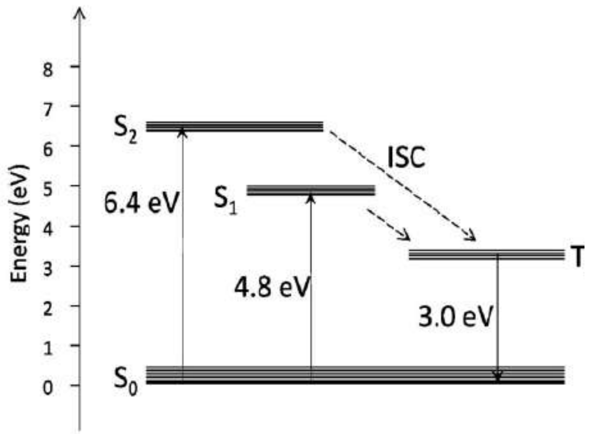


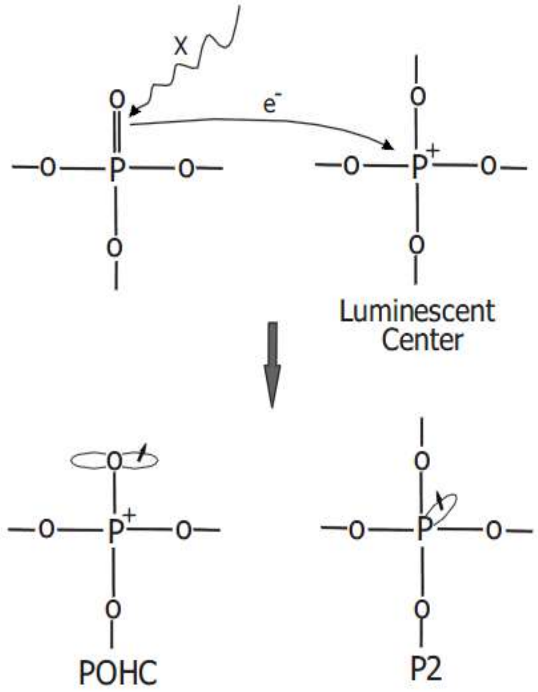
S. Girard, et al., IEEE TNS **55**, 3743, 2008.
S. Girard, et al., JNCS **355**, 1089, 2009.

DIFFERENT TECHNIQUES: LUMINESCENCE

One example : **identification of a paramagnetic P-related defect**







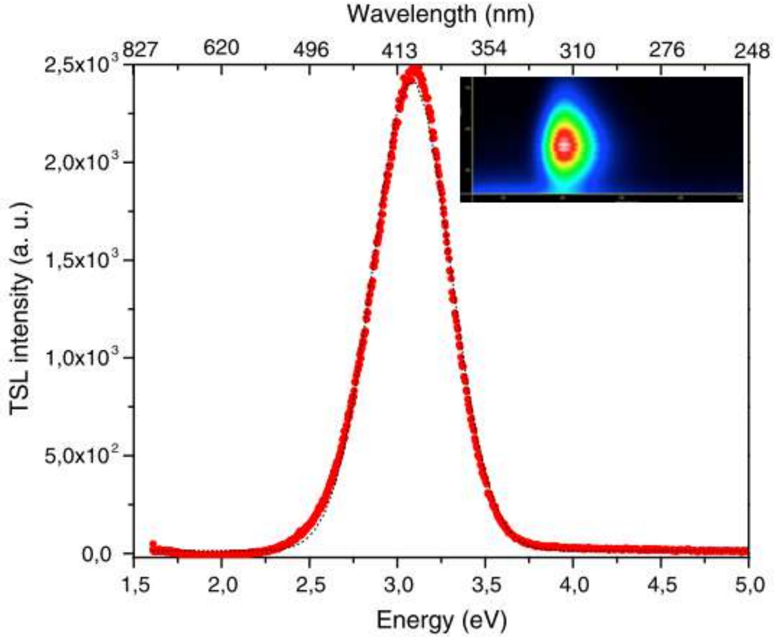
PL, absorption, and ESR measurements:

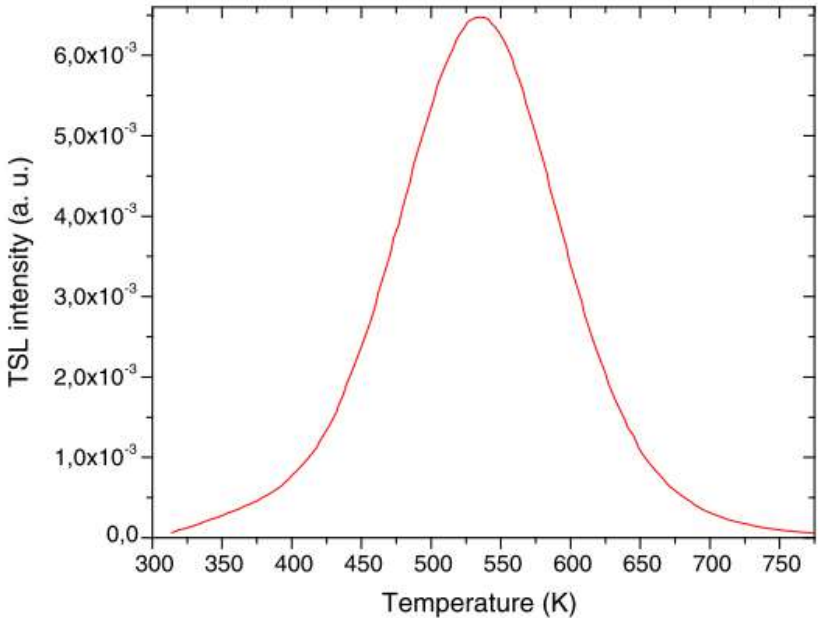
- Emission band peaking at 3.0 eV.
- Excitation consisting in two transitions at 4.8 and 6.4 eV.
- The 4.8 and 6.4 eV excitation channels arise from transitions from the ground to two-excited singlet states, while the 3.0 eV emission is associated to a spin-forbidden transition from an excited triplet to the ground state.
- Eventually, our measurements *lead us to propose a tentative microscopic model of the* defect as a diamagnetic four-coordinated P impurity substitutional to a Si atom.

G. Origlio et al., PRB 80, 205208-1, 2009

- Analyze of the TL glow curve between 300 and 773 K.
- For Ge-doped OF, a main glow peak at 530 K with a characteristic spectral emission centered at 400 nm is found.

*M. Benabdesselam et al., JNCS **360**, 9–12, 2013.*

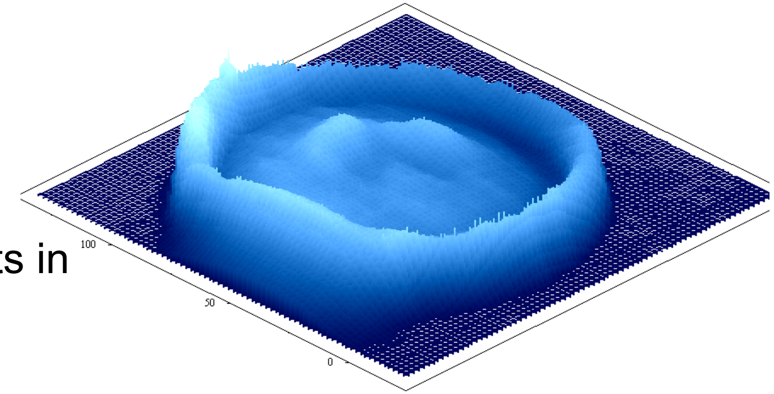


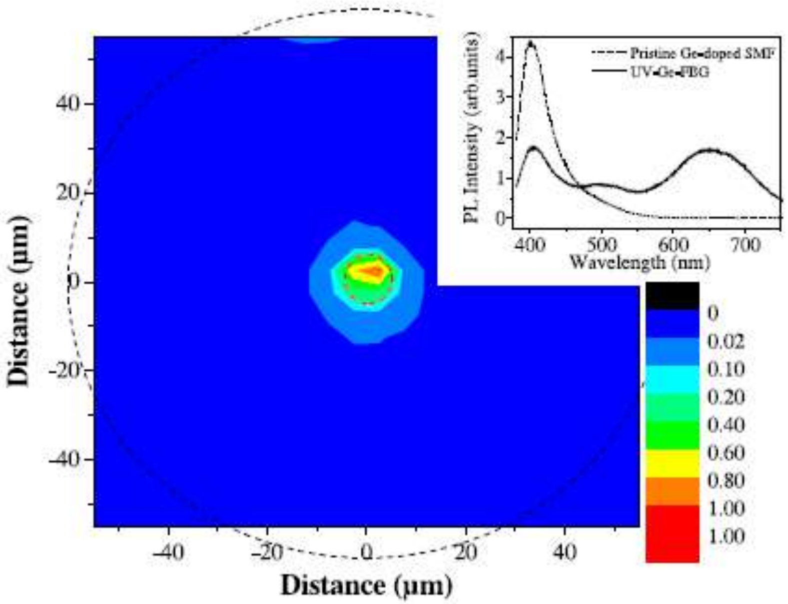


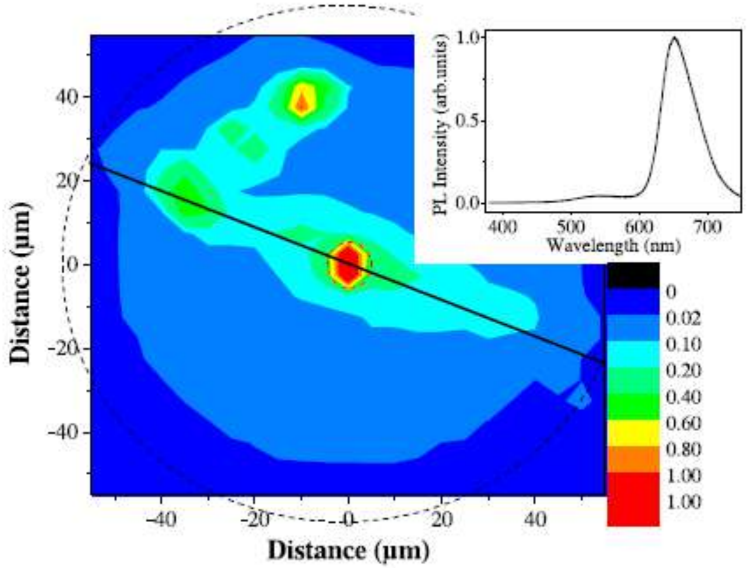
RAMAN OR LUMINESCENCE CONFOCAL MICROSCOPY

Spatial localization of point defects in the transverse cross section becomes possible with Confocal Microscopy of Luminescence (CML) measurements

- Very efficient in association with other spectroscopic techniques
- CML tool is widely used to understand radiation effects in Rare-Earth FOs *and passive optical fibers*





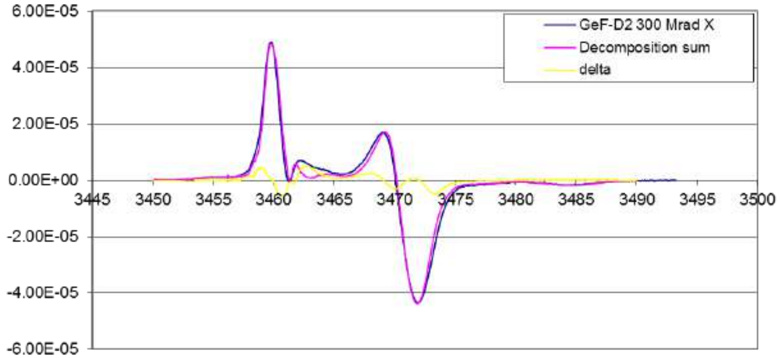


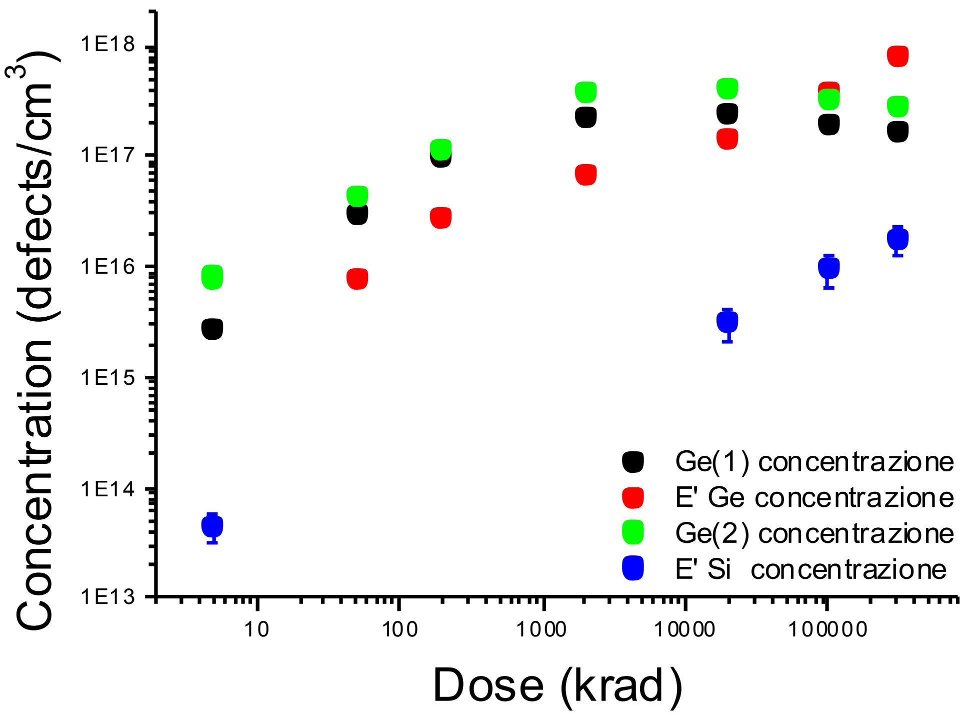
S. Girard, et al., JNCS **351**, 1830, 2005 / IEEE TNS **54**, 1136, 2007
B. Tortech, et al., IEEE TNS **55**, 2223, 2008 /JNCS **355**, 1085, 2009
G. Origlio, et al., NIMB **266**, 2918, 2008 / OL **34**, 2282,2009. A Morana, JLT, **33**, 2646, 2015

DIFFERENT TECHNIQUES: EPR measurements

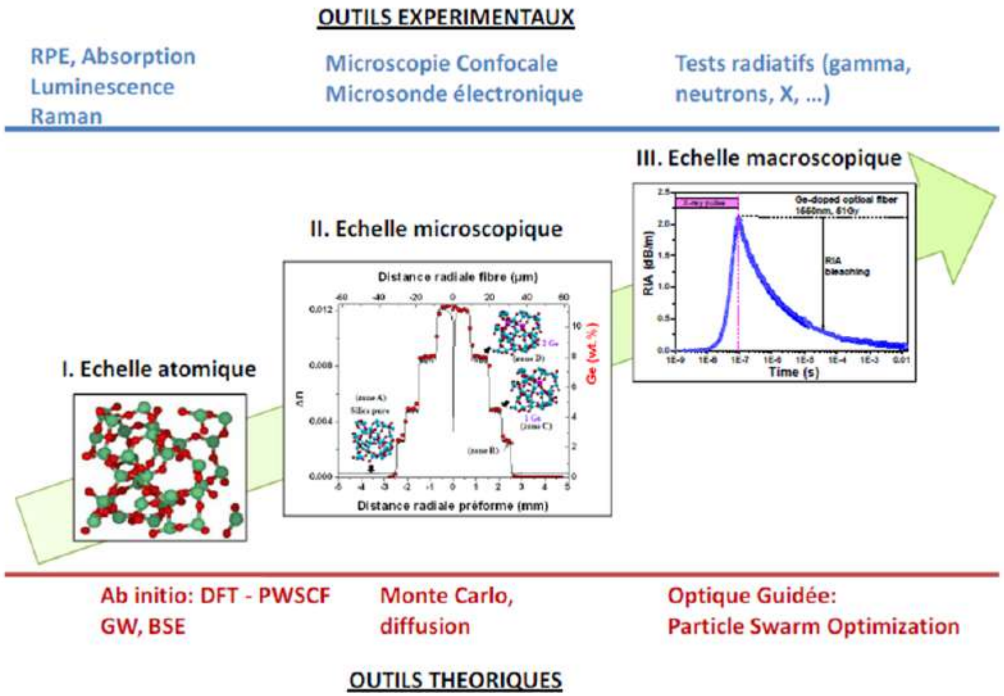
- Electron paramagnetic resonance (EPR) or electron spin resonance (ESR) spectroscopy is a technique for studying materials with unpaired electrons.

- It gives access to the structure and the concentration of paramagnetic defects ➔ the kinetics of the EPR Changes are correlated with OA or OL changes under treatments allowing to associate defect structure and optical properties





Future advances in the design of radiation-hardened optical fibers will benefit from **on-going coupled simulation experiments approach**



Understanding of the radiation induced mechanisms at the different scales ➔ **control of these degradation mechanisms**

In future, we planned to be able to develop a **predictive simulation chain** allowing to evaluate the degradation of a given fiber into future facilities or new space environments

Joint Research Team
CEA DAM DIF - LabHC

S. Girard et al., IEEE TNS 55(6), 3743-3482, 2008.
S. Girard e al., IEEE TNS 55(6), 3508-3514, 2008.
N. Richard et al., IEEE TNS. 61(4),1819 - 1825, 2014.

- Most of applications in fusion/fission environments (data transfer, diagnostics, …) are limited by the RIA phenomena ➔ **Radiation Hard Optical Fibers exist today for most of IR applications at MGy dose**

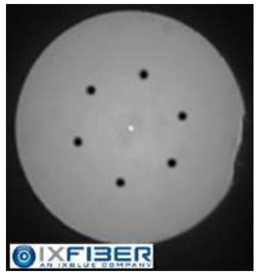
IXFIBER AN IXBLUE BRAND

Draka

- More efforts are in progress to have a **full product** (cable, connectors,…) **qualification for operation in harsh environments**

- Fibers for **UV operation for fusion/ fission** or able to survive to extreme neutron fluences & temperature are still under development.

- New fiber generations have still to be evaluated (PCF, HACC multicore,…) for space and nuclear industry



Today, functionalization of OF is targeted in order that in addition to data transfer, they could monitor environmental parameters

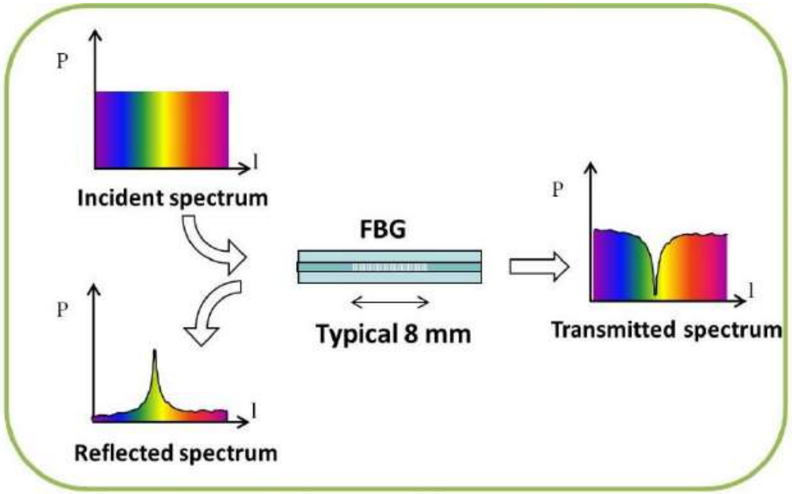
TOWARDS THE FUNCTIONALIZATION OF OPTICAL FIBERS: RECENT ADVANCES ON FIBER SENSING

- **Fiber Bragg Gratings (strain, temperature, ….)**
- Raman (T)
- Brillouin (T, strain,…)
- Rayleigh (T, strain, …)

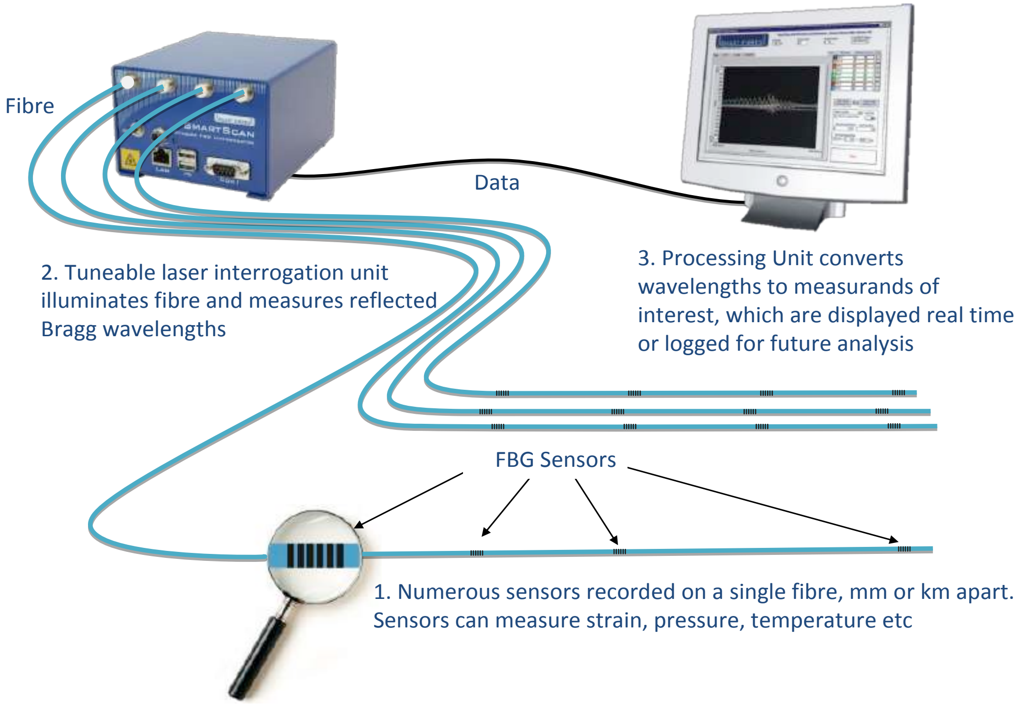
- Dosimetry
  - RIA (*active, distributed*)
  - TL (*passive*)
  - RIL, OSL (*active punctual*)

- FBG Temperature & Strain Sensing

- **Advantages:**
  - Small size (Ø~100µm)
  - Light weight
  - Resistance to electromagnetic interference
  - No need of electrical power at the sensing point
  - Quick response (<1s)
  - Multiplexing



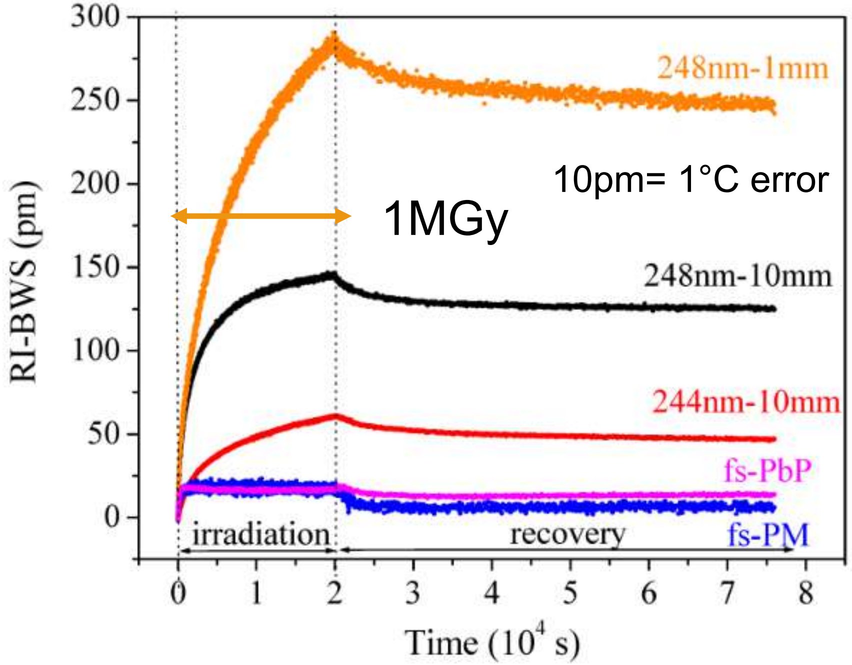
http://www.fbgs.com



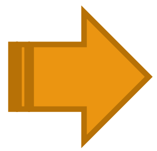
Radiation effects on FBG properties

- **Limitations in radiative environments:**
  - Degradation of the fiber properties under radiation (RIA)
  - Influence on the FBG properties:
    - **Amplitude:** possible FBG erasing under irradiation ➔ loss of functionality
    - **Bragg Wavelength Shift:** error on T measurements ➔ degradation of the sensor performance

A. Gusarov et al., IEEE TNS, 60, pp. 2037-2053 (2013)

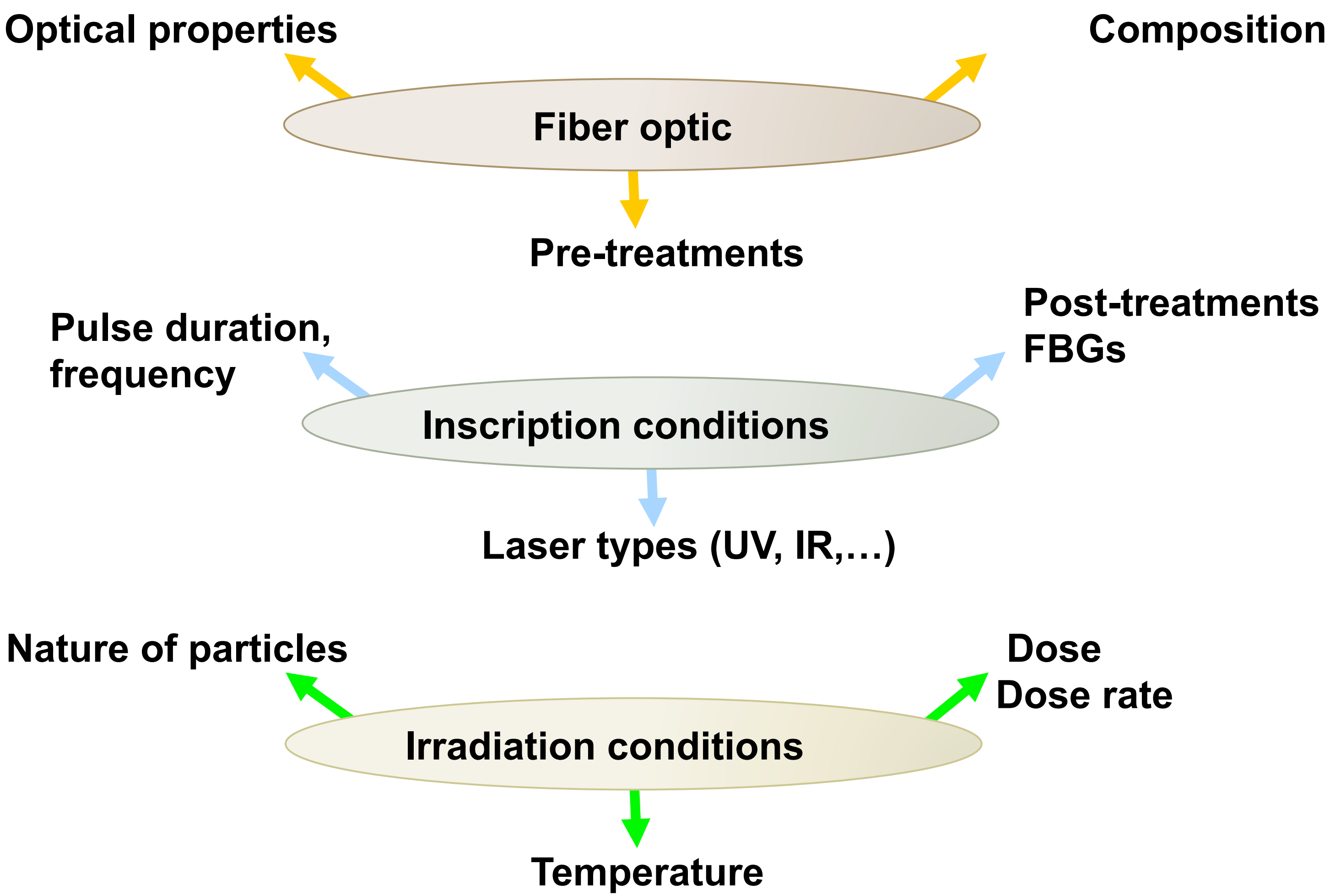


A. Morana *et al.*, Opt Express, 23(7), 8663 (2015)



What is the best FBG technology for MGy dose levels (nuclear industry)?

Parameters impacting the FBG radiation response



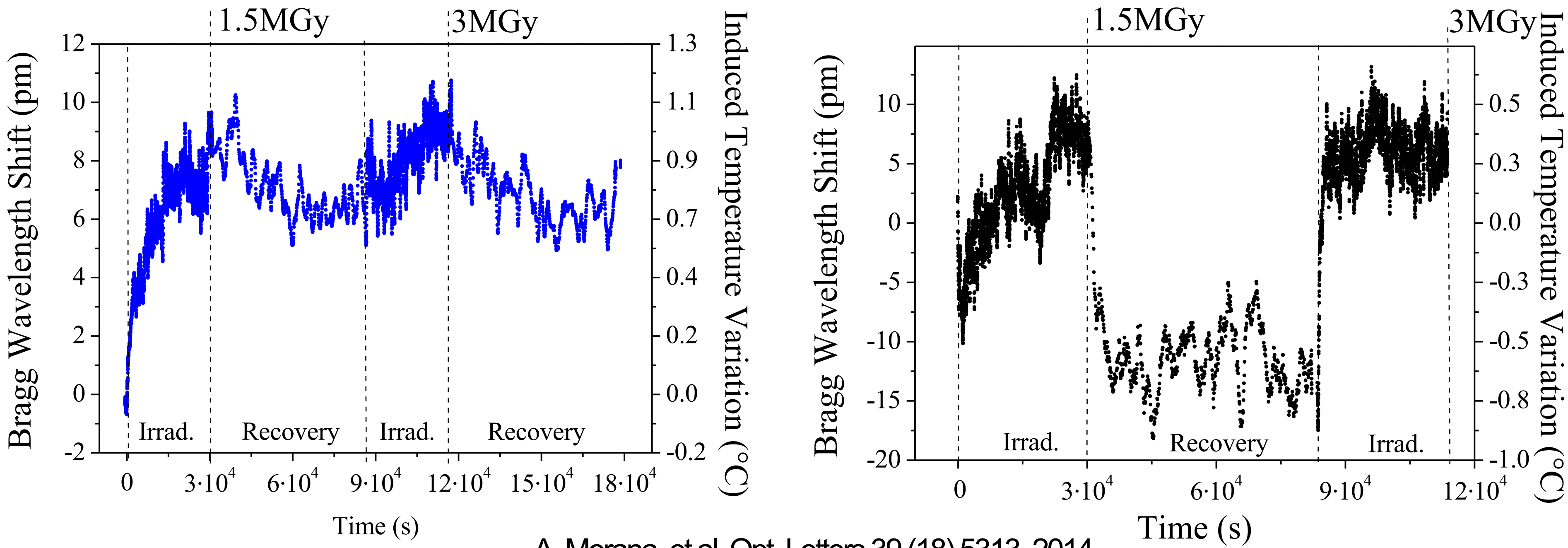
We identified a procedure to develop radiation hardened FBGs for high temperature operation (up to 250°C)

AREVA LABORATOIRE HUBERT CURIEN UMR • CNRS • 5516 • SAINT-ETIENNE **patent (Dec. 2013)**

LabHC- AREVA RH-FBGs are made with fs lasers following a patented procedure

- **ROOM TEMPERATURE (~25°C)**

HIGH-T (~230°C)



A. Morana, et al. Opt. Letters 39 (18) 5313, 2014

➡ These RH FBGs also present the best response to high-T and high fast neutron fluence

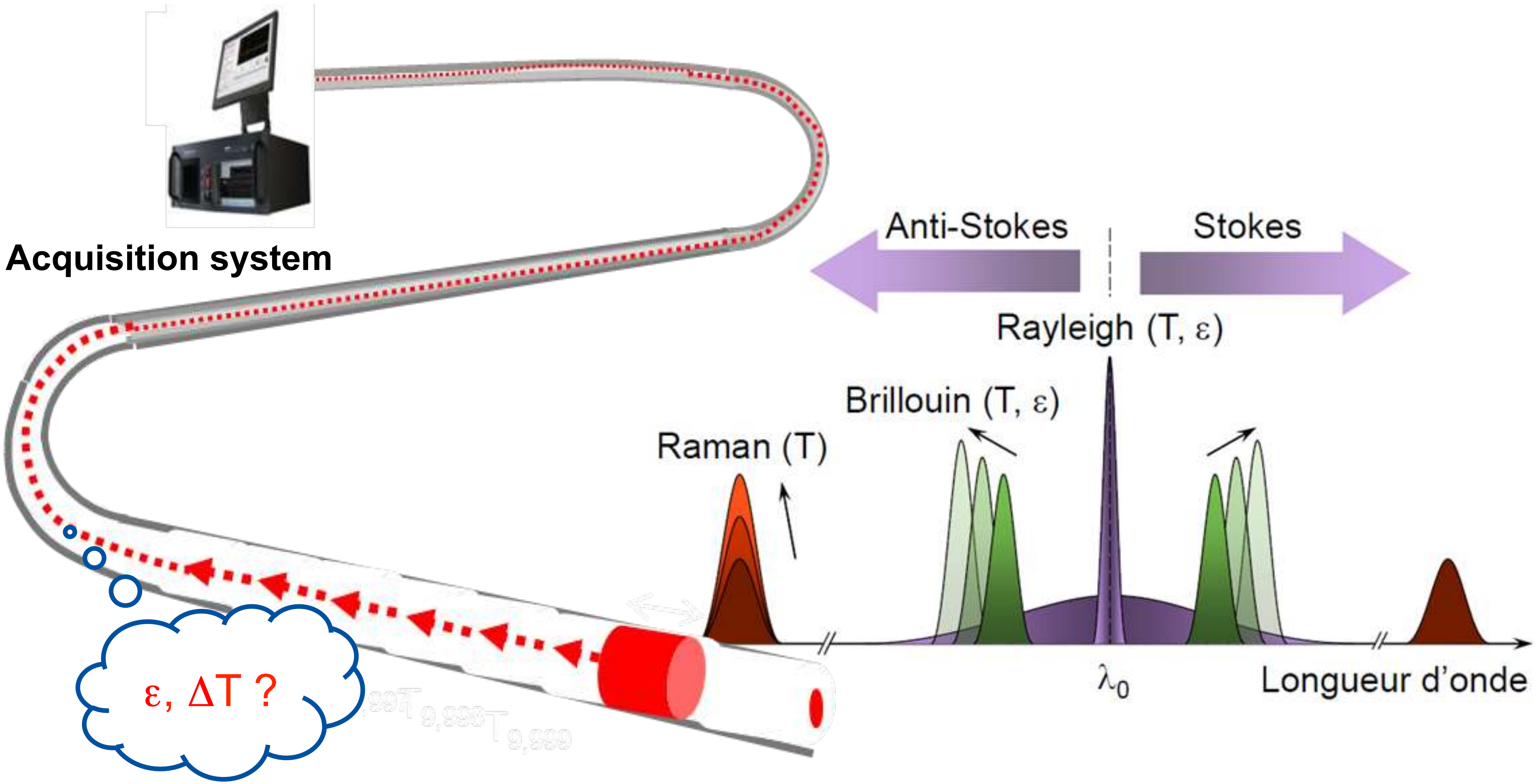
TOWARDS THE FUNCTIONALIZATION OF OPTICAL FIBERS: RECENT ADVANCES ON FIBER SENSING

- Fiber Bragg Gratings (strain, temperature, ….)
- **Raman (T)**
- **Brillouin (T, strain,…)**
- **Rayleigh (T, strain, …)**

Distributed sensing:
thousands of sensing points

- Dosimetry
  - RIA (*active, distributed*)
  - TL (*passive*)
  - RIL, OSL (*active punctual*)

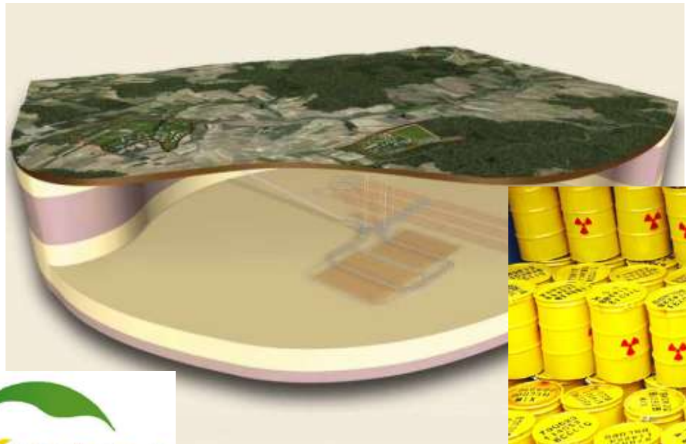
Distributed sensing based on backscattered light into an OF

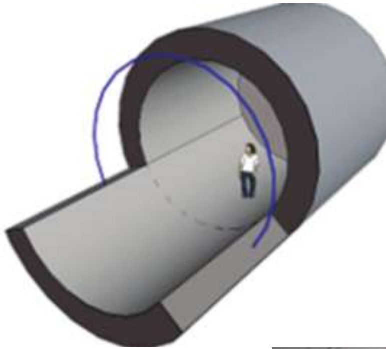


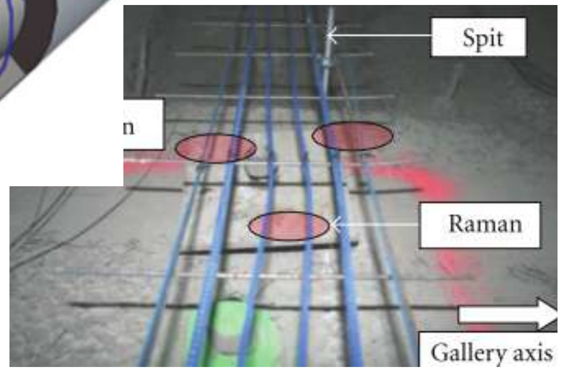
Raman is sensitive to **T** only ➔ spatial resolution of about 1m, over kms
Brillouin is sensitive to **T, strain** ➔ spatial resolution of about 1m, over kms
Rayleigh is sensitive to **T, strain** ➔ spatial resolution of about 100µm, over 100m

Example: ANDRA application

- Temperature and strain monitoring will be implemented in the envisioned French geological repository for high- and intermediate-level long-lived nuclear wastes.

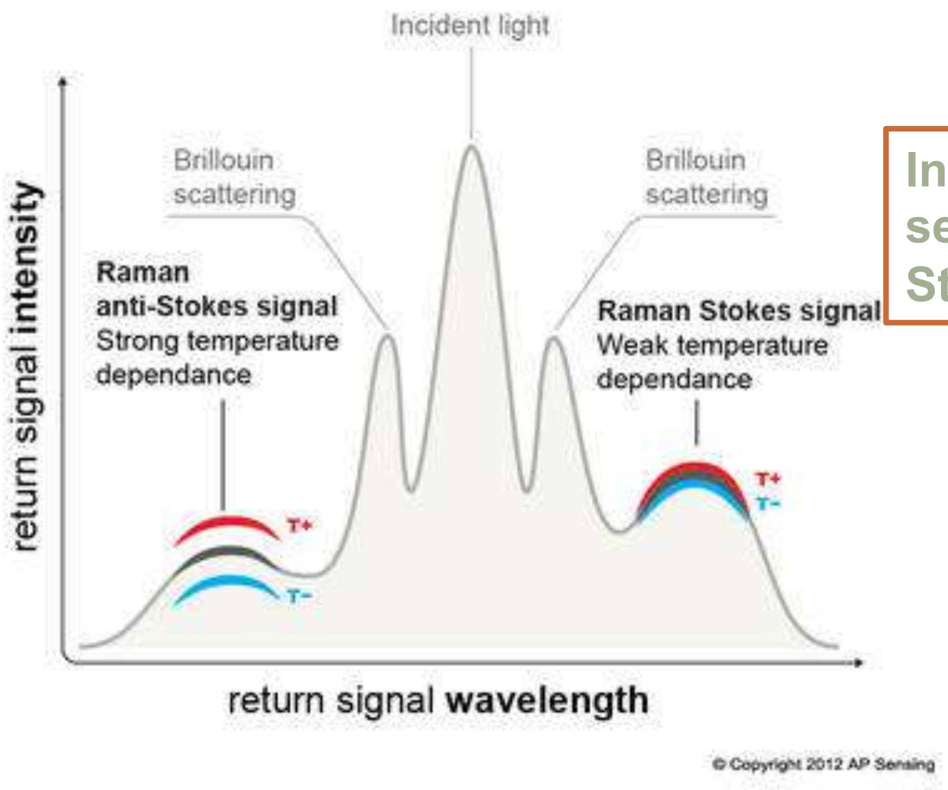






➢ Gamma radiation and hydrogen **release** from nuclear wastes can however affect the **Brillouin and Raman measurements**.

➡ **Investigations of radiation effects on Raman and Brillouin sensors to provide T, strain discrimination**



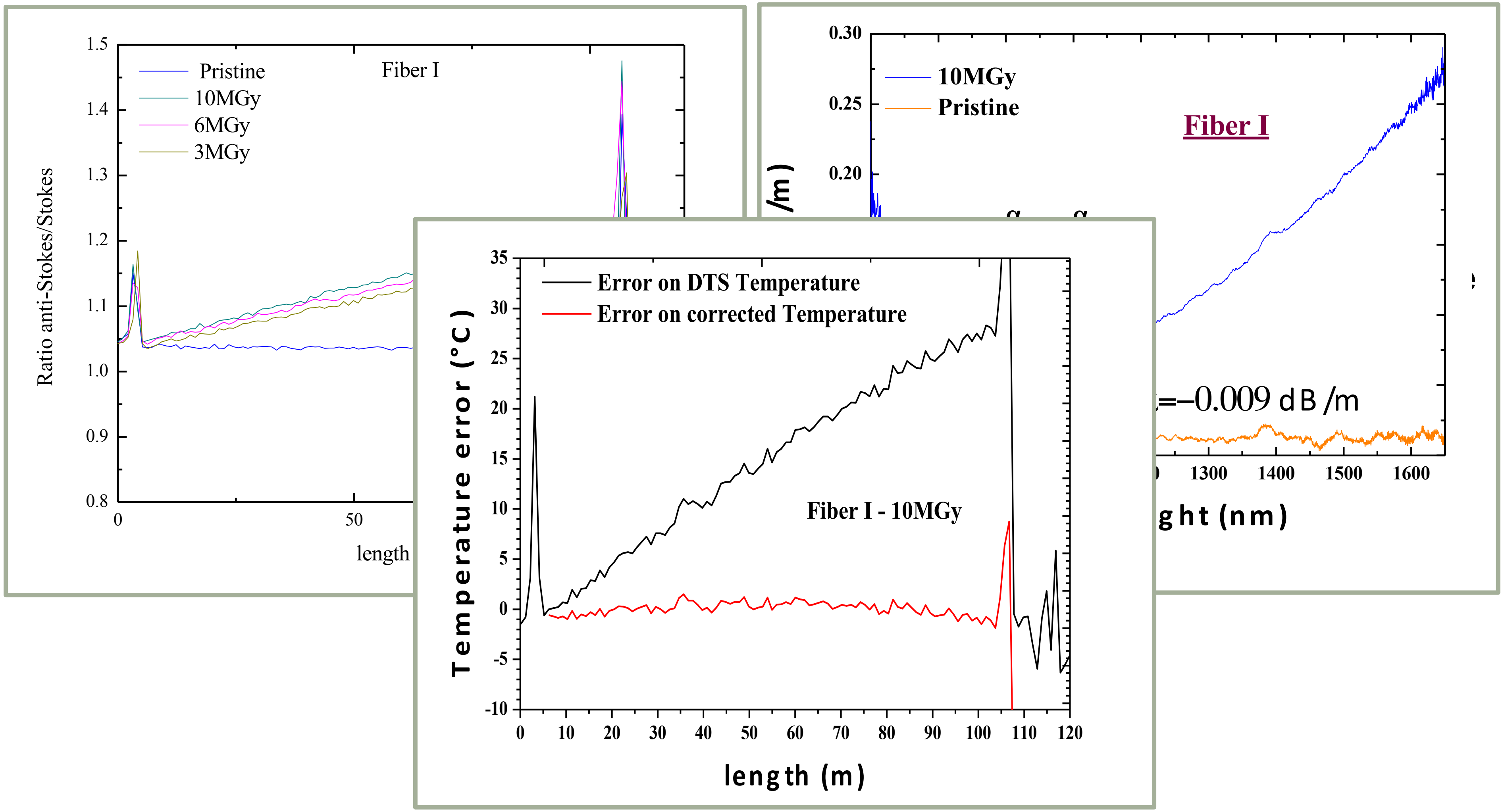
Intensity of the Anti-Stokes line is more sensitive to the temperature than the Stokes line one ➔ T monitoring

$R(T)=I_{as}/I_{s}=(\nu_{as}/\nu_{s})^{4}\, e^{-\gamma/}$

The assumption, that $\delta\alpha=(\alpha_{as}-\alpha_{s})$ remains constant or uniform along the fiber length could be inappropriate, especially in radiation environment.

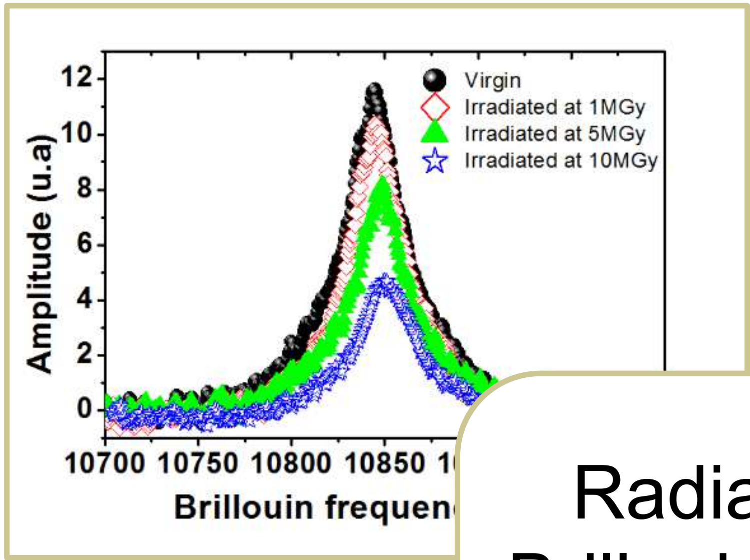
A. Fernandez Fernandez, et al, IEEE TNS, 5**2**, (6) pp 2689-1694 (2005).

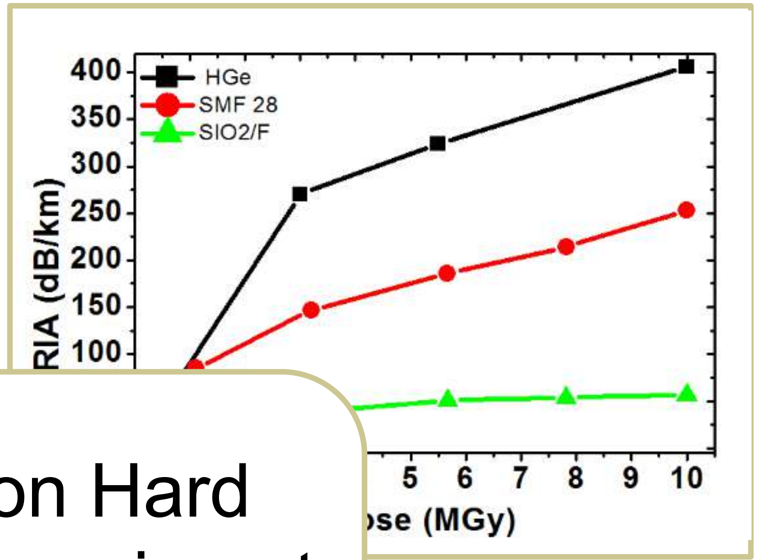
Raman distributed temperature measurements: radiation effects



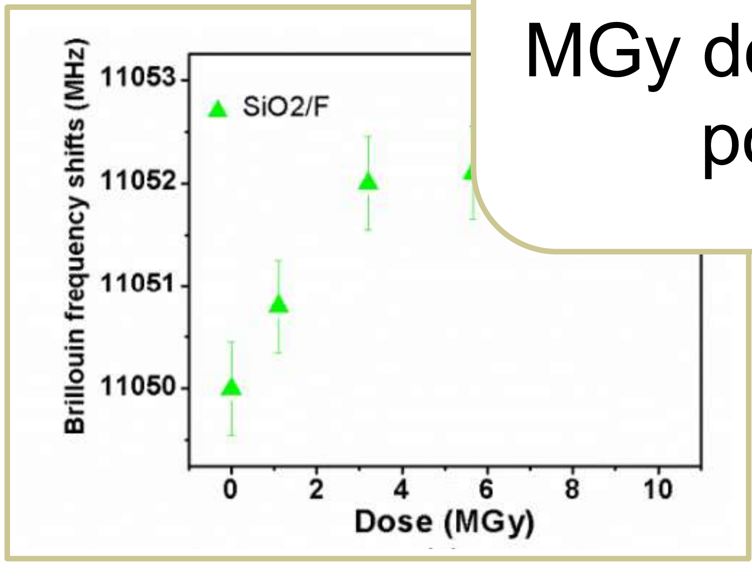
C. Cangialosi, et al., IEEE TNS, vol,61 (6), pp,3315 - 3322 , 2014.
C. Cangialosi, et al., IEEE/OSA JLT, in press, 2015 (10.1109/JLT.2014.2388453)

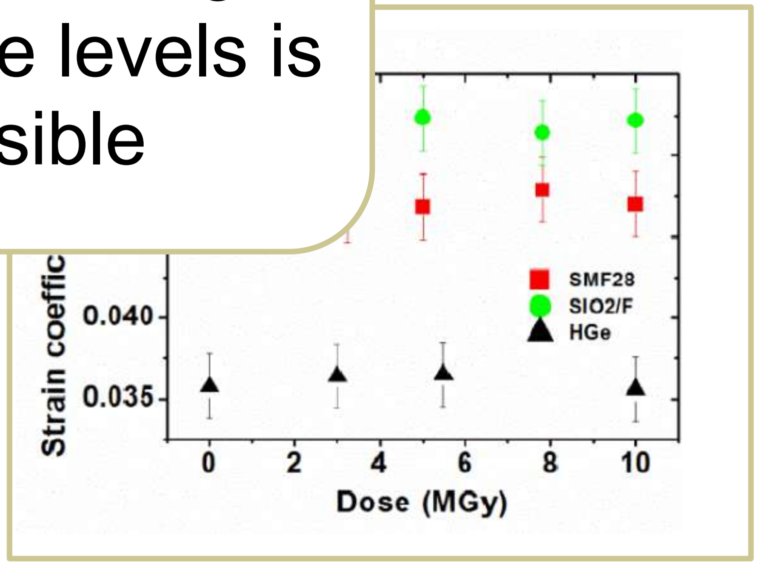
Brillouin distributed temperature measurements: radiation effects





Radiation Hard Brillouin sensing at MGy dose levels is possible

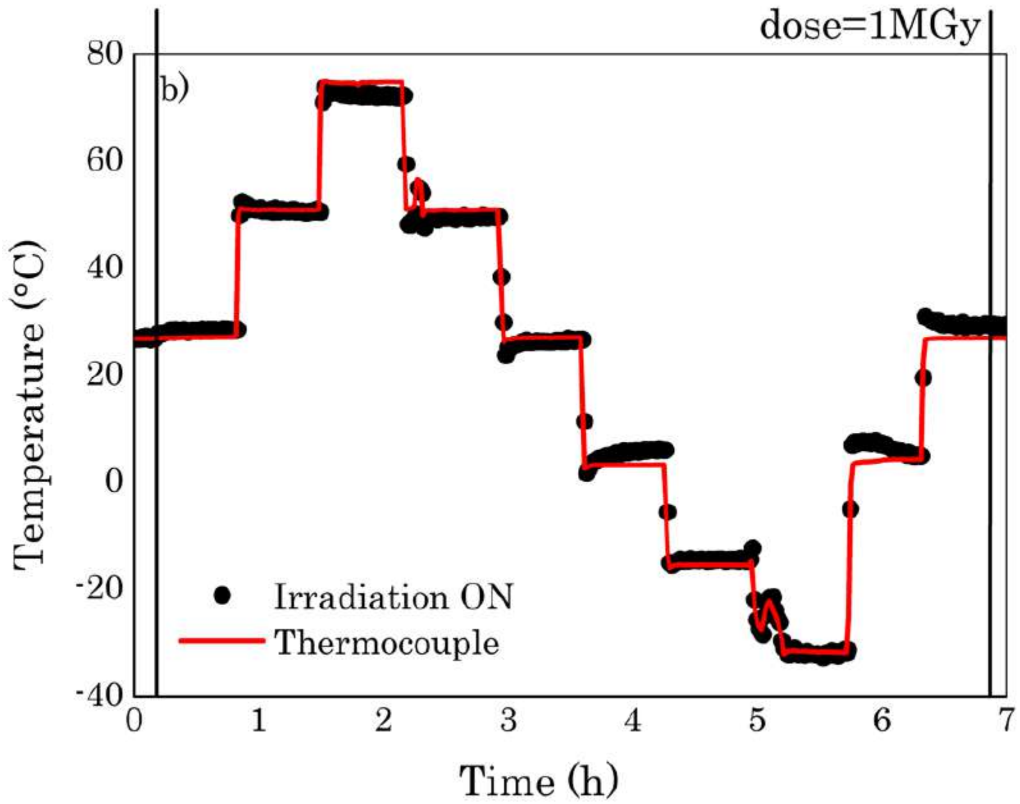




X. Phéron, *et al.*, Opt. Express vol, 20, pp, 26978-26985 (2012)

OFDR reflectometry is a very promising technique with a high spatial resolution (100µm over 70m for LUNA OBR4600)

- ❑ Limited knowledge about radiation effects on this technology (Alexey Faustov, PhD <100kGy TID)
- ❑ Rayleigh scattering is not affected by irradiation, at least up to 10MGy
- ❑ **<u>Only RIA limits the fiber sensing range</u>**



⇨ **Very recent results demonstrated the potential of this technique for monitoring T, strain in nuclear facilities**

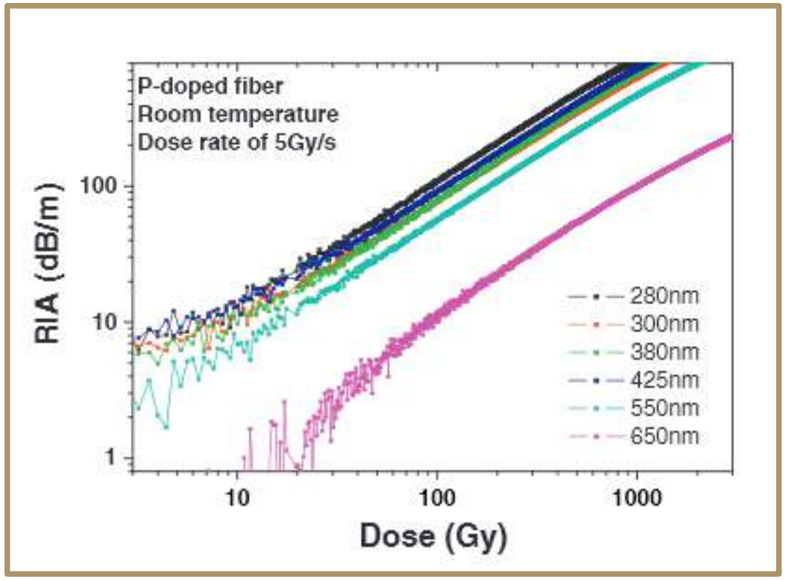
S. Rizzolo, et al., Optics Express, vol.23 (15), 18998 , 2015.
S. Rizzolo, et al., Optics Letters, in press, 2015 ; S. Rizzolo et al., IEEE TNS, in press, 2015.
AREVA – LabHC, 2015 pending patents

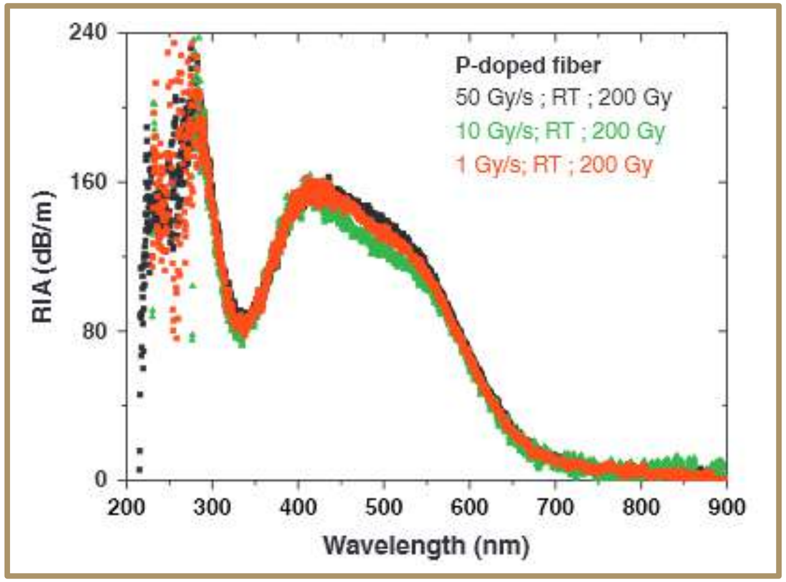
TOWARDS THE FUNCTIONALIZATION OF OPTICAL FIBERS: RECENT ADVANCES ON FIBER SENSING

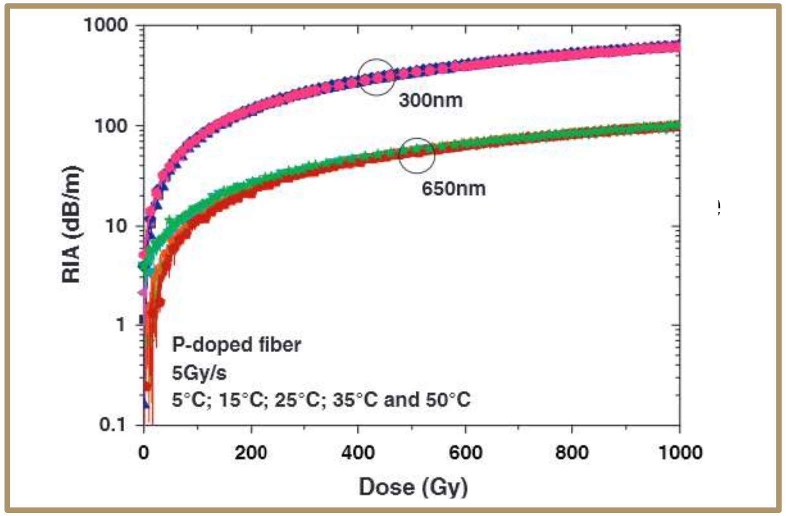
- Fiber Bragg Gratings (strain, temperature, ….)
- Raman (T)
- Brillouin (T, strain,…)
- Rayleigh (T, strain, …)

- **Dosimetry**
  - **RIA (*active, distributed*)**
  - **TL (*passive*)**
  - **RIL, OSL (*active punctual*)**

- ❑ Feasibility of using P-doped OFs to monitor the TID levels **<u>during an irradiation</u>**. (Other groups: Al-doped fibers)
- ❑ Coupled with reflectometry (OTDR, OFDR)➔ **<u>TID distribution along the OF</u>**







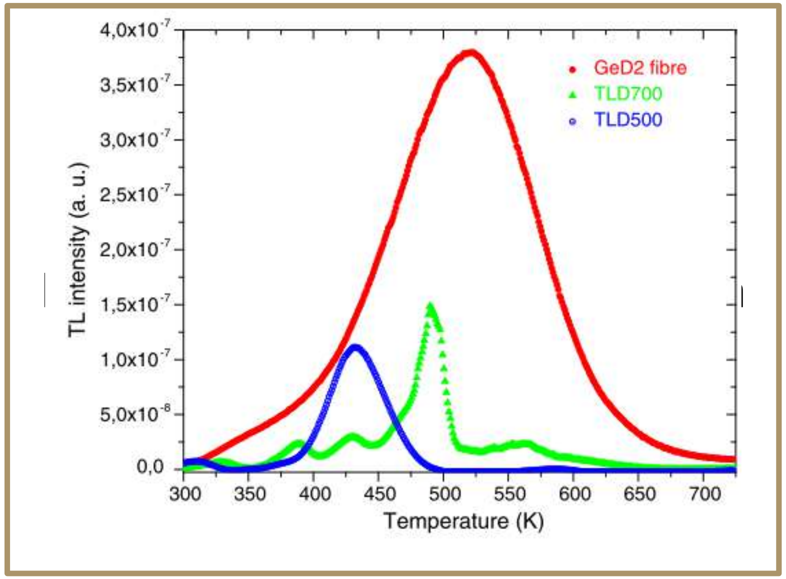
Remaining issues for fission/fusion facilities:

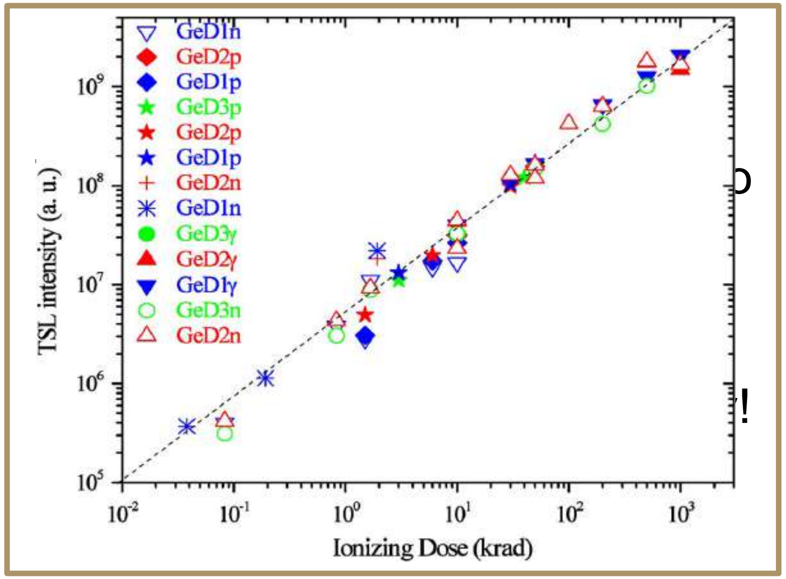
- Saturation at TID> 50kGy
- Reset of the dosimeter?
- …

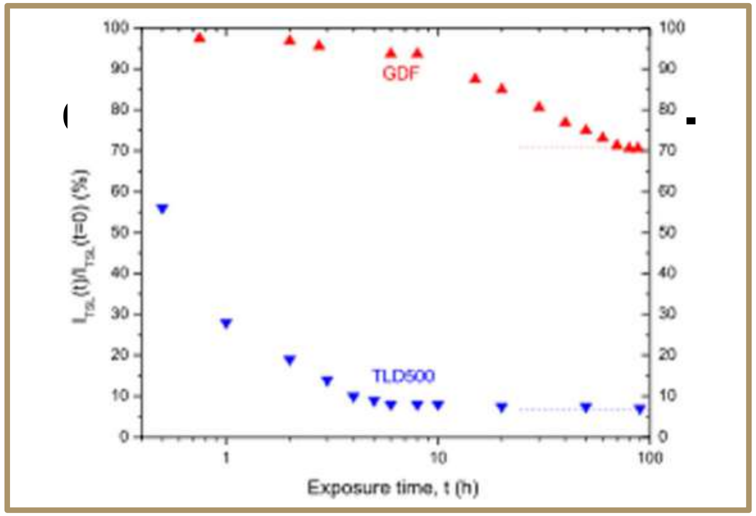
S. Girard, et al., JNCS, vol. 357(8-9), pp. 1871-1874, 2011.

Thermoluminescence (TL) Dosimetry with Ge-doped OF

- TL Dosimetry is widely used (eg. TLD500), Ge-doped fibers have shown exceptional properties with respect to COTS dosimeters







Possible applications:

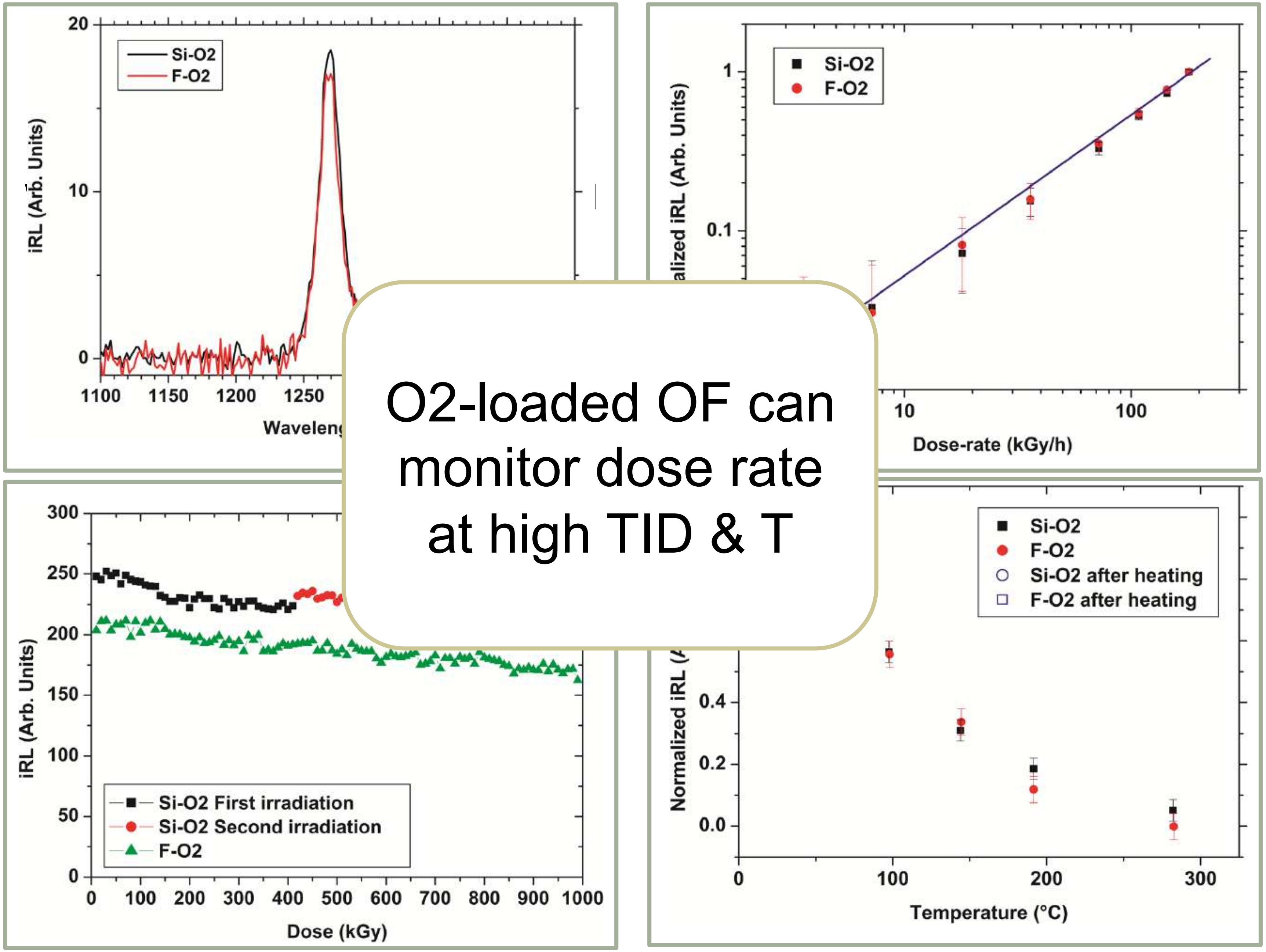
- Medical applications
- High energy physics faciilties
- …

Perspectives:

- OSL for online TID measures?

M. Benabdesselam, et al., JNCS, 360, 9, 2013
M. Benabdesselam, et al., IEEE TNS, 60(6), 4251, 2013,
M. Benabdesselam, et al., IEEE TNS, 61(6) 3485, 2014.

TSL/Dosimetry with Ge-doped OF: from medical to nuclear applications



O2-loaded OF can monitor dose rate at high TID & T

D. Di Francesca et al., Applied Physics Letters, 105, 183508, 2014

CONCLUSIONS

- Optical fiber and fiber-based sensors are quickly integrated in facilities encountering radiations
- Future challenges concern the **functionalization of these fibers** to monitor measurands such as T, strain, pressure, liquid level, vibrations,….
- Overcoming these challenges will be possible through a **coupled simulation/experiments approach** to identify/predict the basic mechanisms describing the radiation effects in dielectrics

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