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AVANTAGES ET LIMITATIONS À L'INTÉGRATION DES FIBRES OPTIQUES ET DES CAPTEURS À FIBRES OPTIQUES DANS LES ENVIRONNEMENTS RADIATIFS

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2ème Journée Thématique du Club Fibres Optiques et Réseaux
Les capteurs et l'instrumentation à fibres optiques
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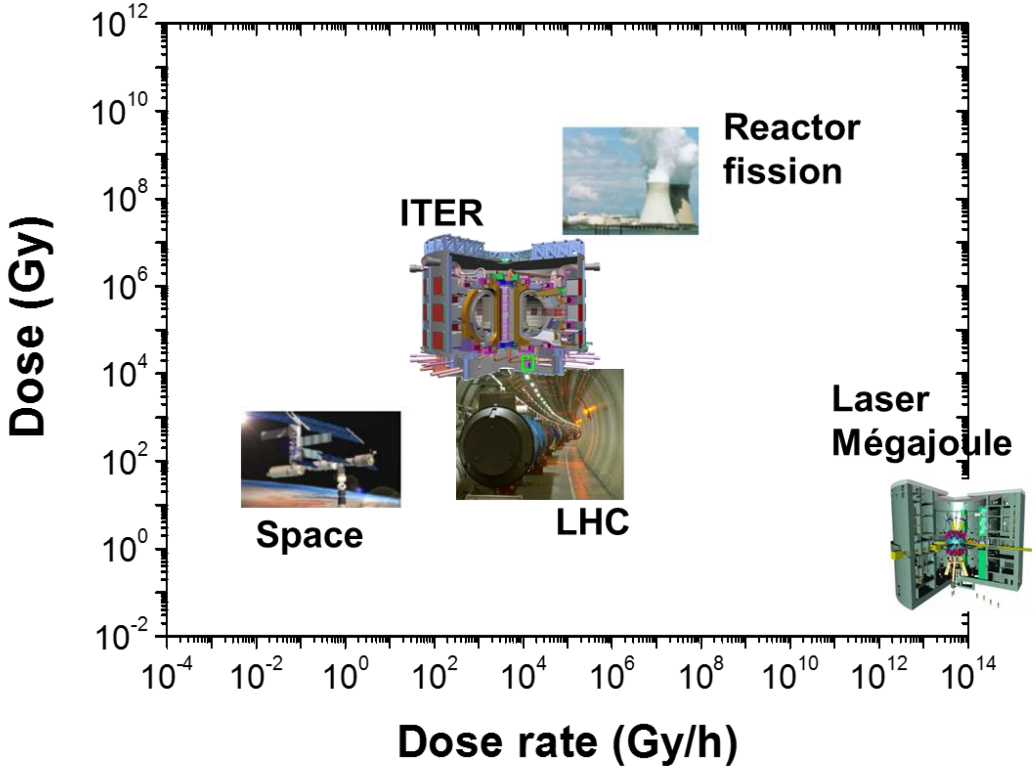
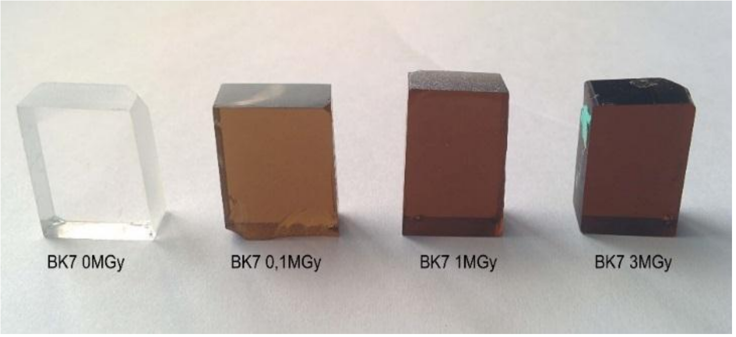
Silica-based optical fibers present **several advantages** compared to copper cables for use in nuclear environments

1. **Electromagnetic immunity**
2. **High bandwidth/ multiplexing capability**
3. **Low attenuation**
4. **Low weight and volume**
5. **High temperature resistance**



➔ 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)**

Courtesy
B. Brichard
(SCK-CEN)

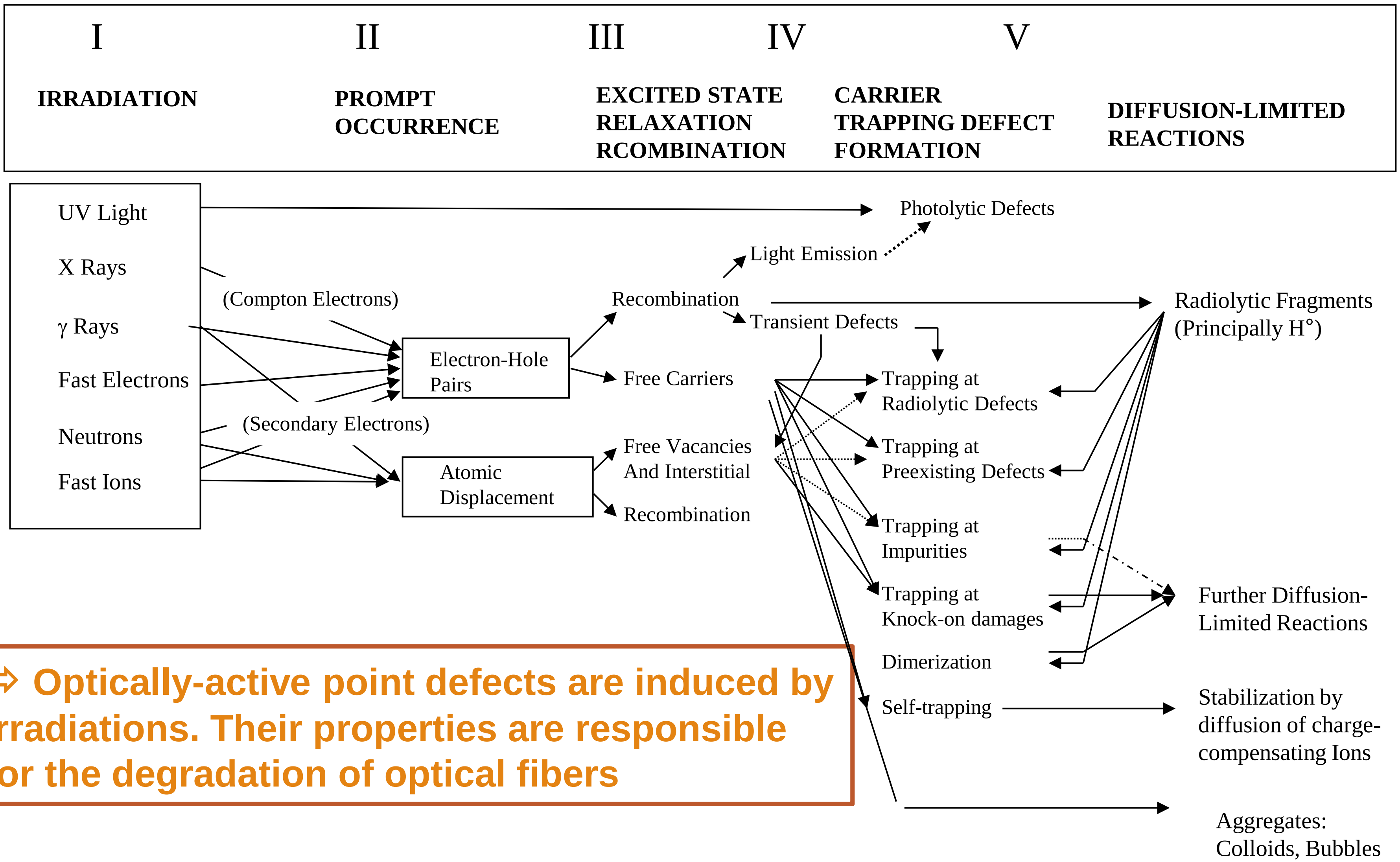
3. **Compaction**

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

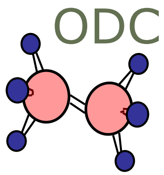
- **The relative influences of these 3 mechanisms depend on the <u>radiation environment</u> associated with the fiber-based system and on the <u>targeted application</u> (fiber sensors)**

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

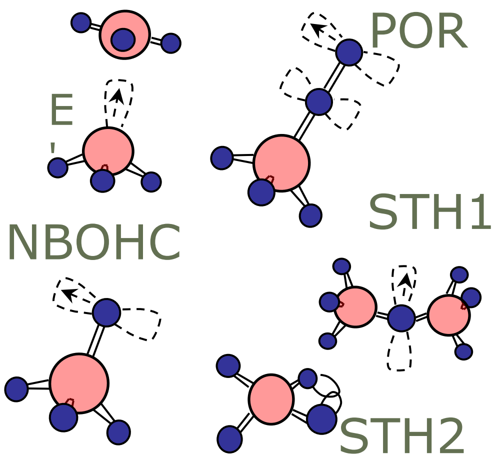
Griscom D.L. SPIE vol. 541, 1985

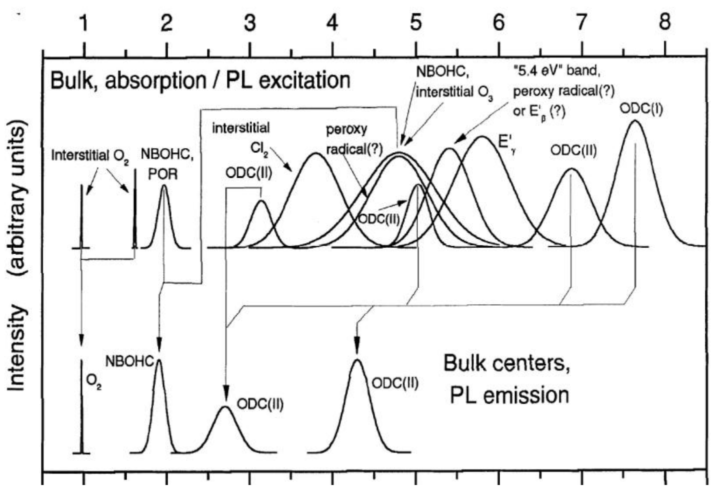


⇨ Optically-active point defects are induced by irradiations. Their properties are responsible for the degradation of optical fibers

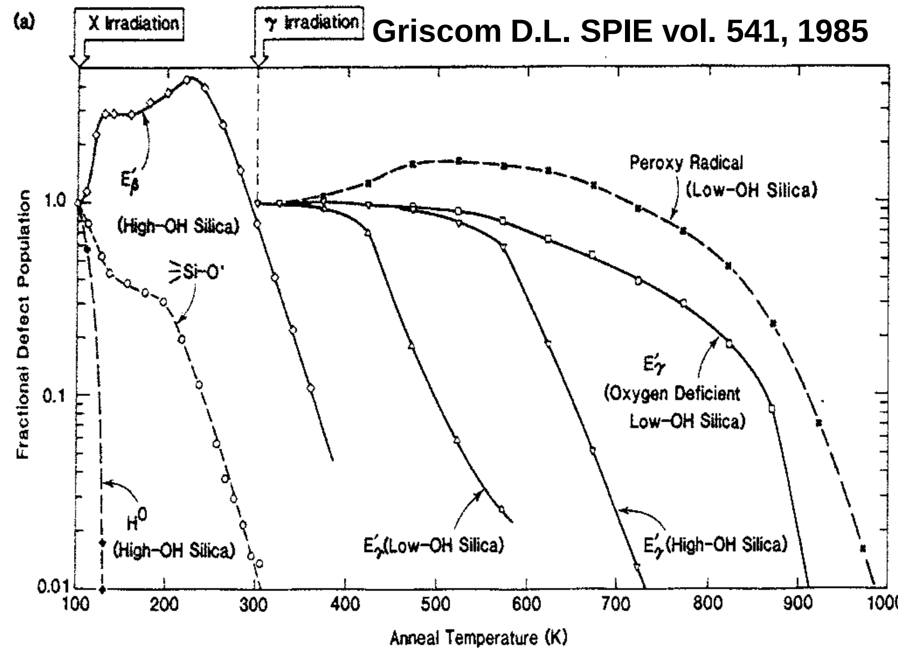


Optical and energy properties of these point defects explain the complexity of the fiber radiation-response





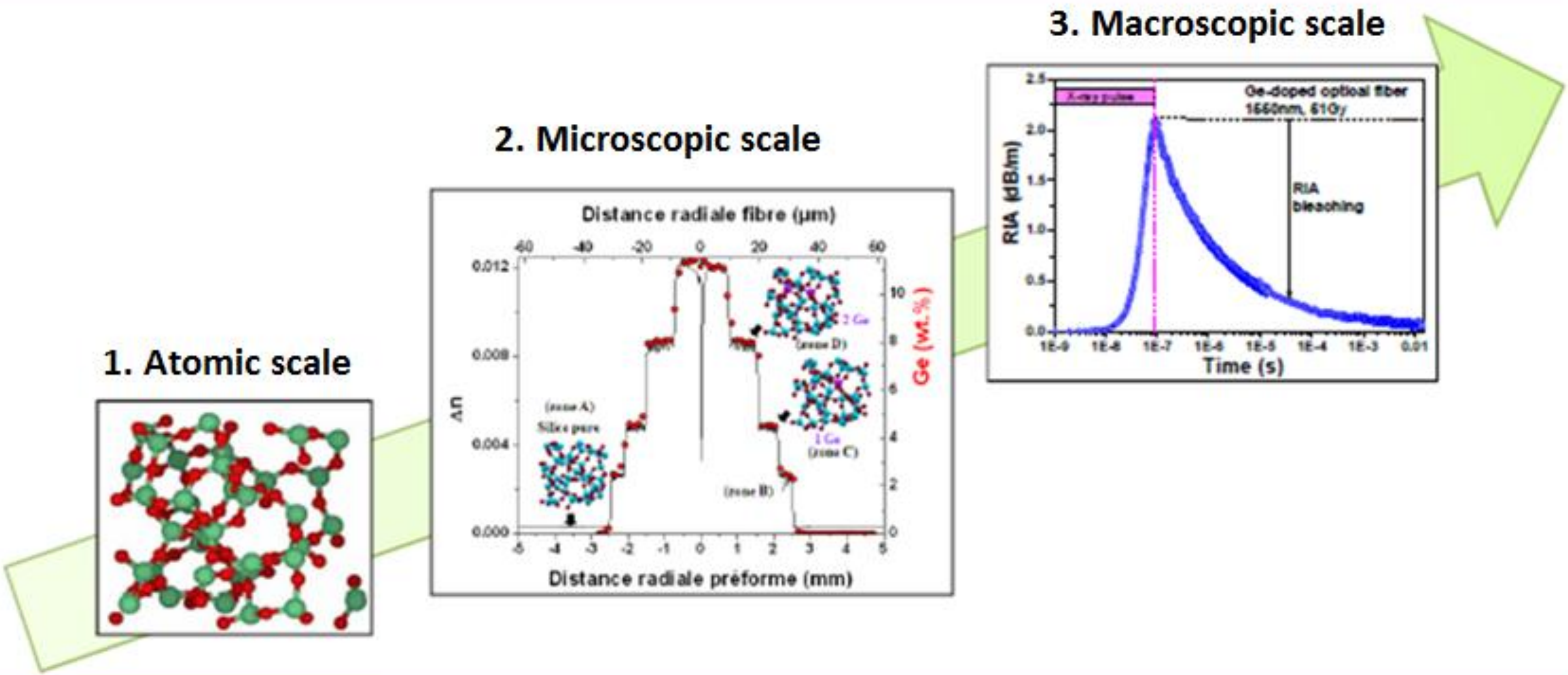
L. Skuja; NATO Book Chapter, 2000



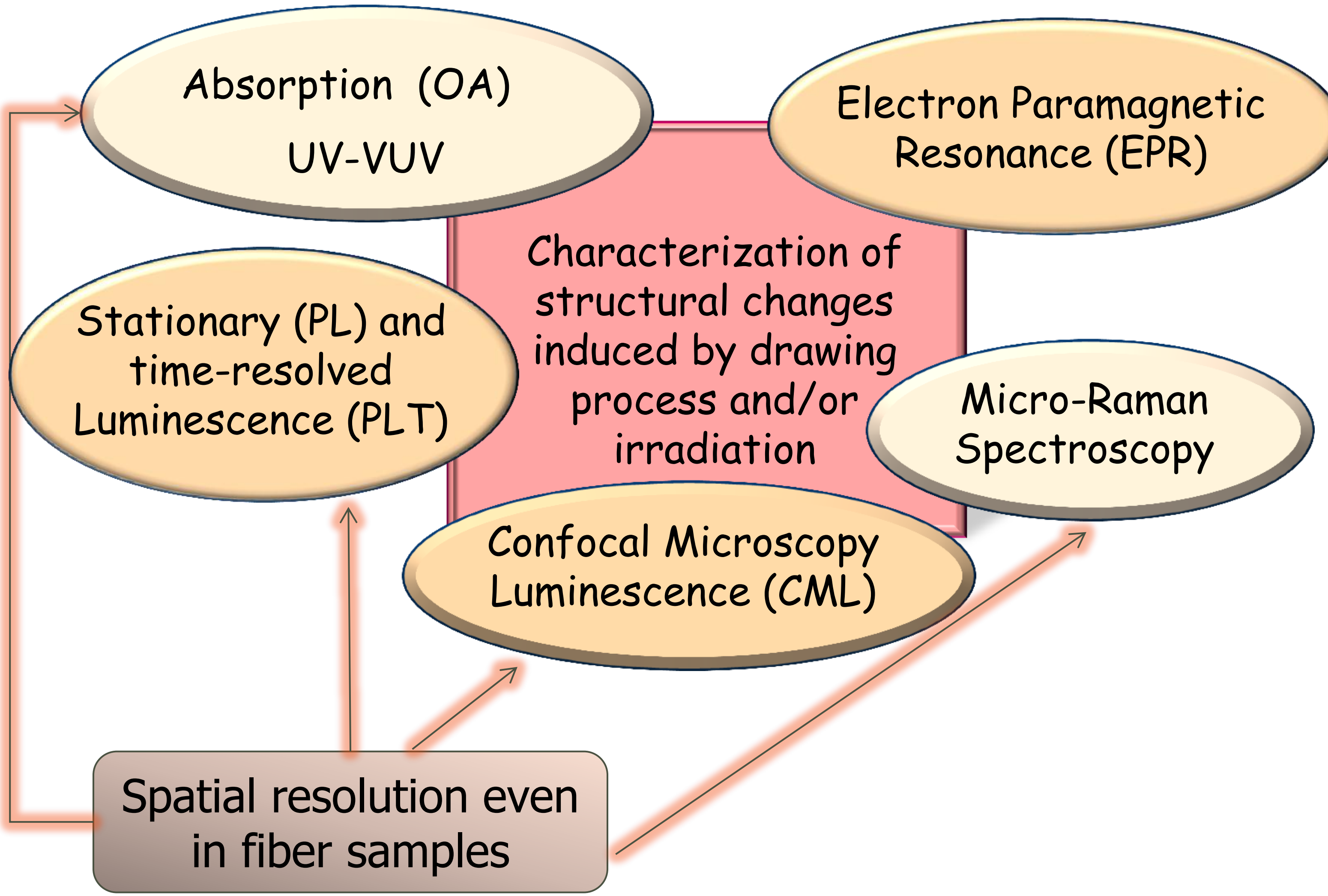
Griscom D.L. SPIE vol. 541, 1985

- Each parameter affecting the stability, generation efficiency or optical properties of these point defects will affect the fiber radiation response.
- **Too complex to be yet predictable!**

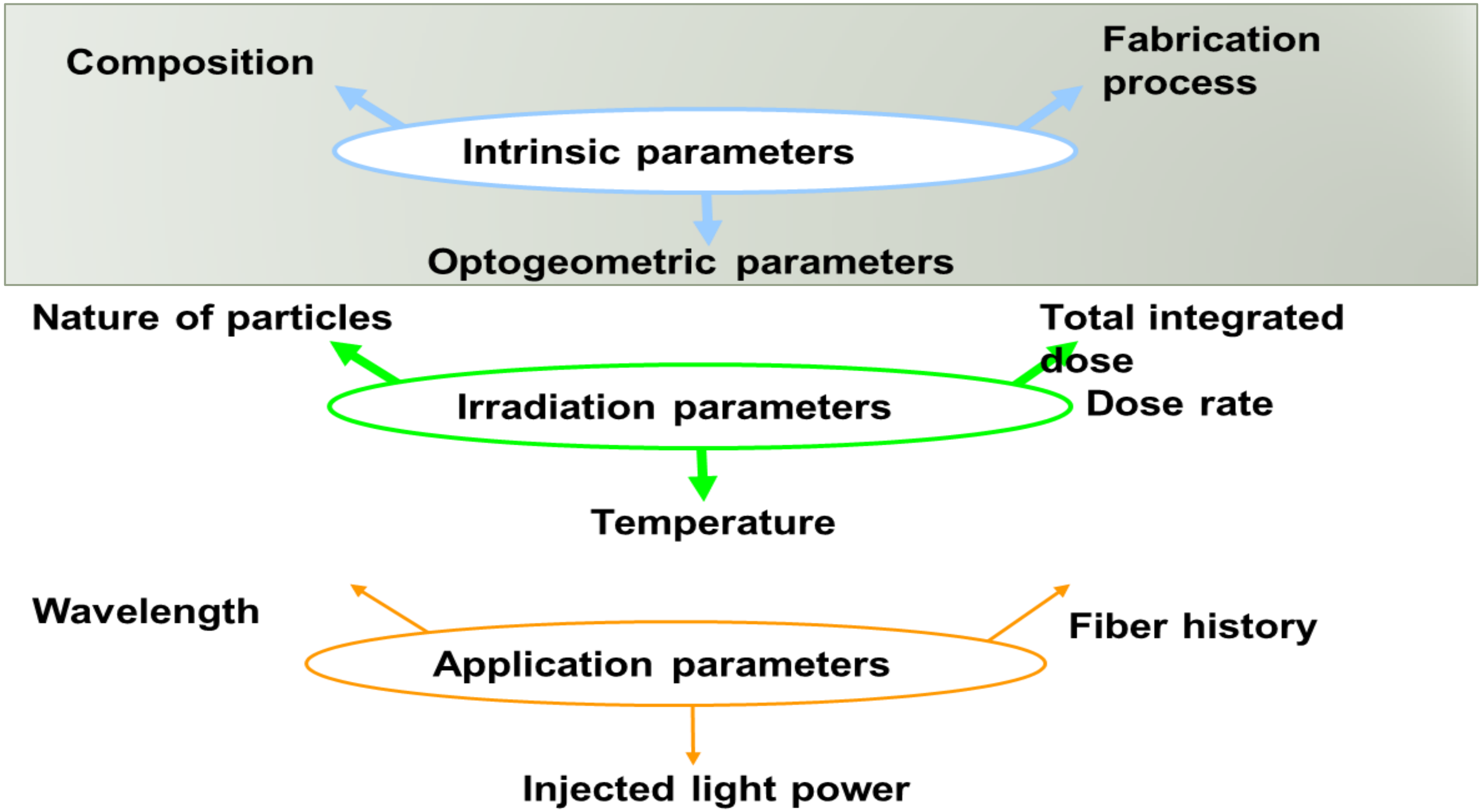
Our approach:
A multiscale - coupled experience / theory



Analysis Techniques

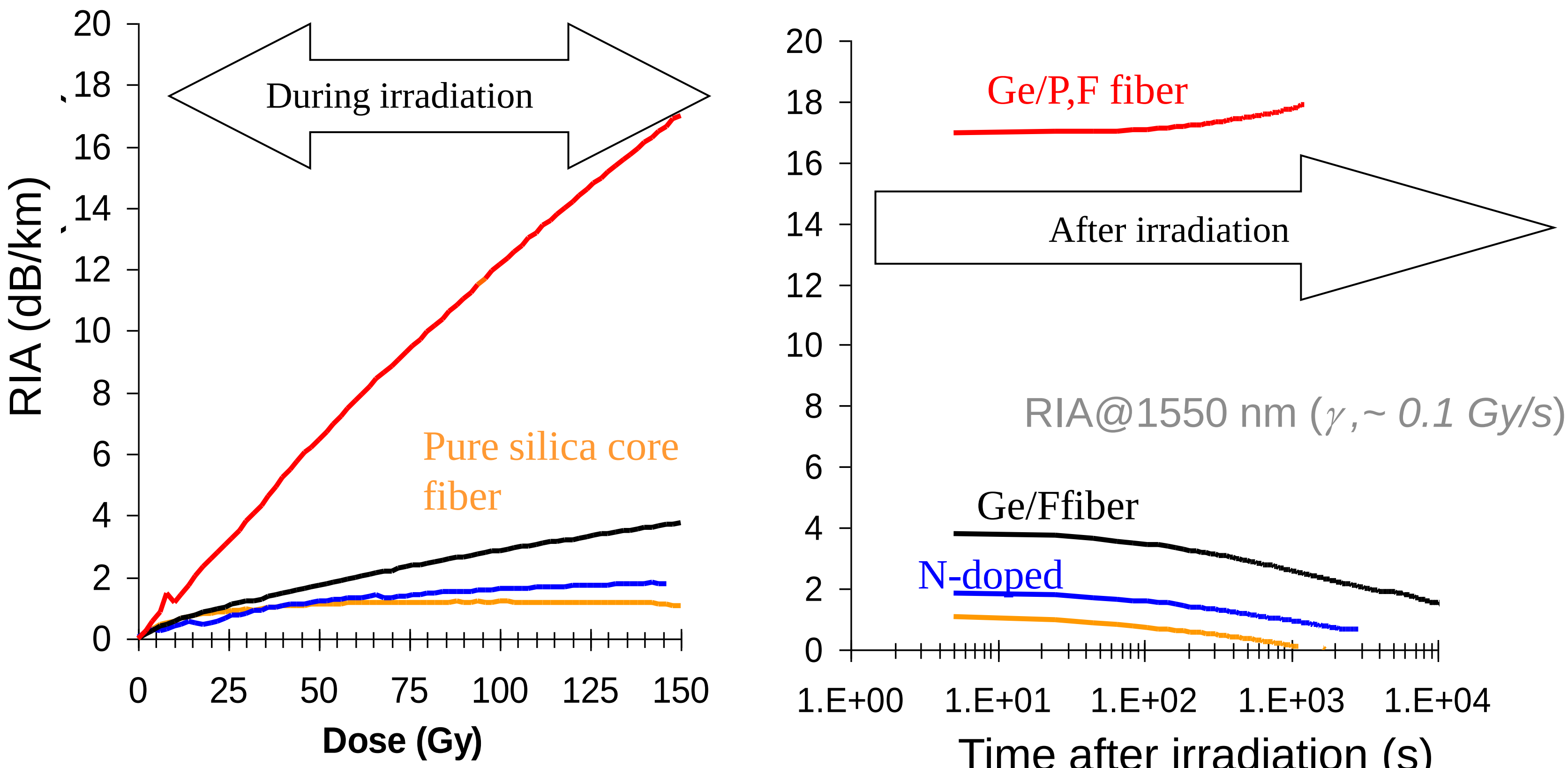


Numerous parameters, intrinsic or extrinsic to the fiber influence its radiation response



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

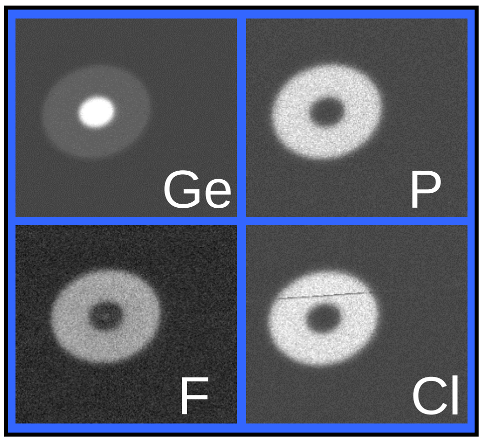
Fiber sensitivity strongly depends on the fiber composition: core dopants, *process parameters are less impacting*



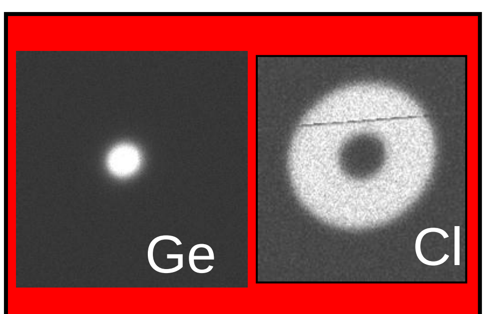
No ideal composition exists, their relative RIA levels depend on the radiation environments, fiber profile of use…

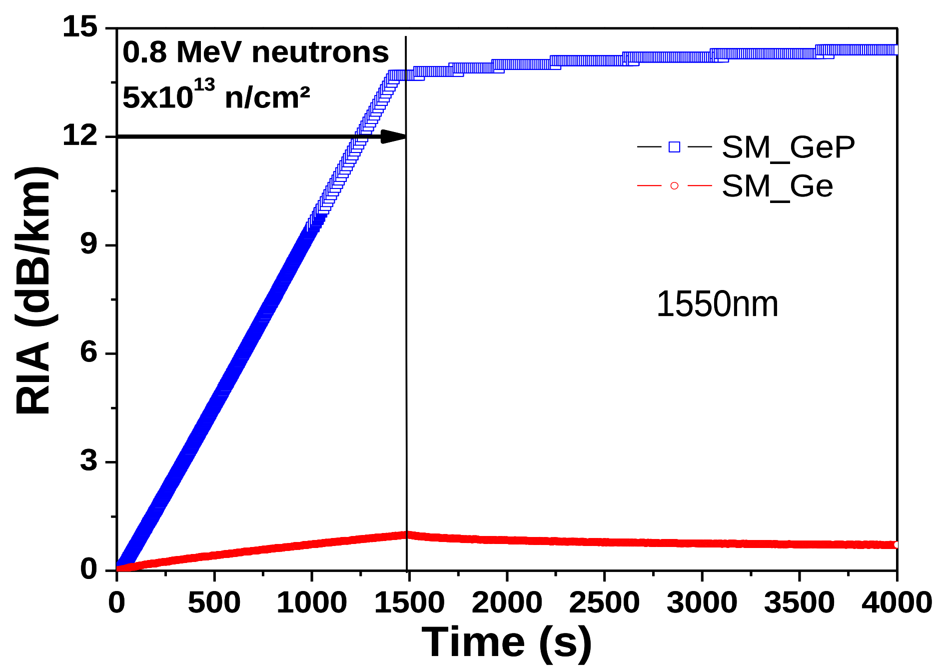
Fiber sensitivity strongly depends on the fiber composition: cladding dopants, stœchiometry, impurities, …

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



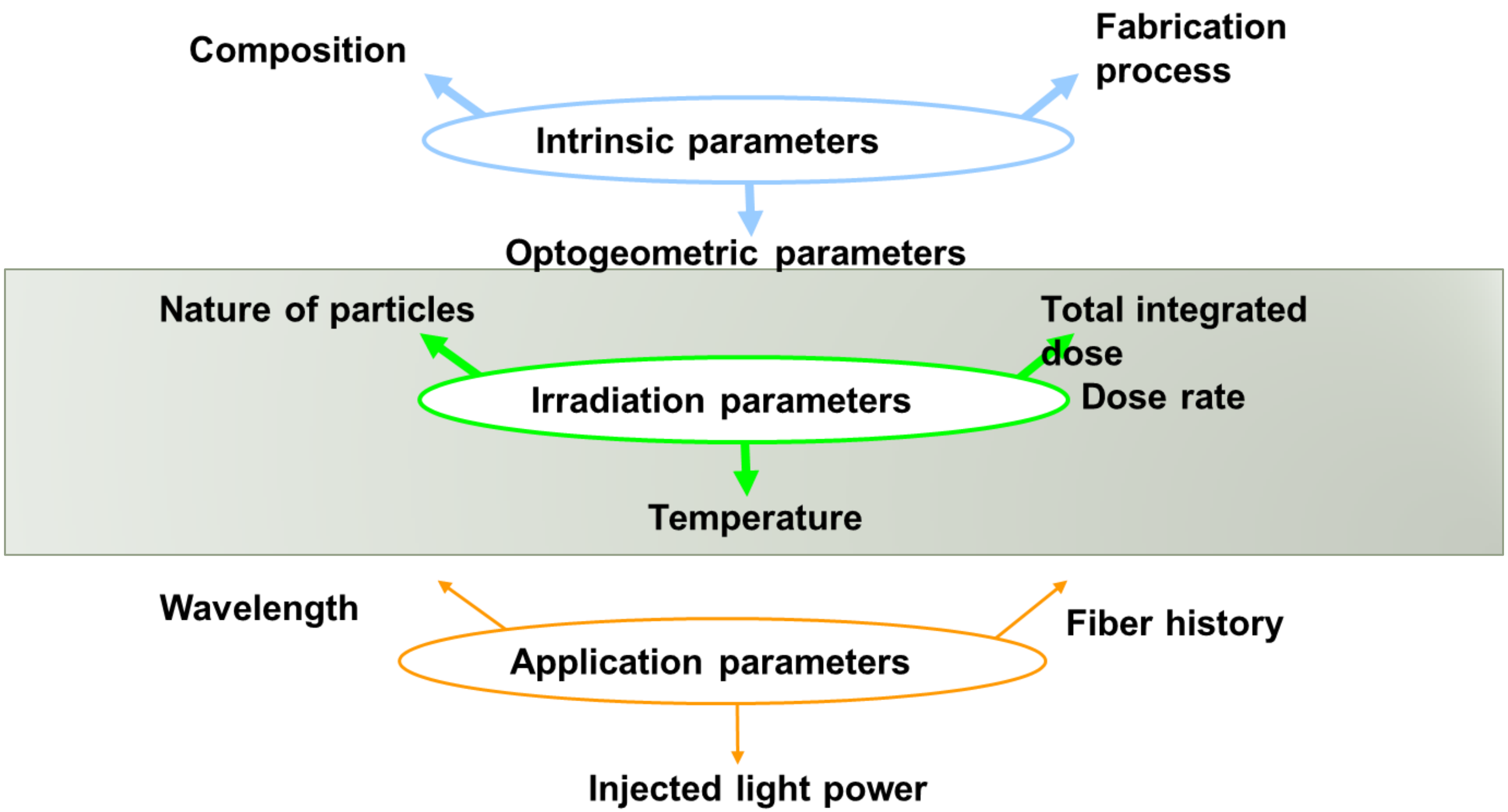
2 Telecom SMF with the same reference but different cladding compositions





Fibers with the same reference done at different factories can present extreme radiation responses

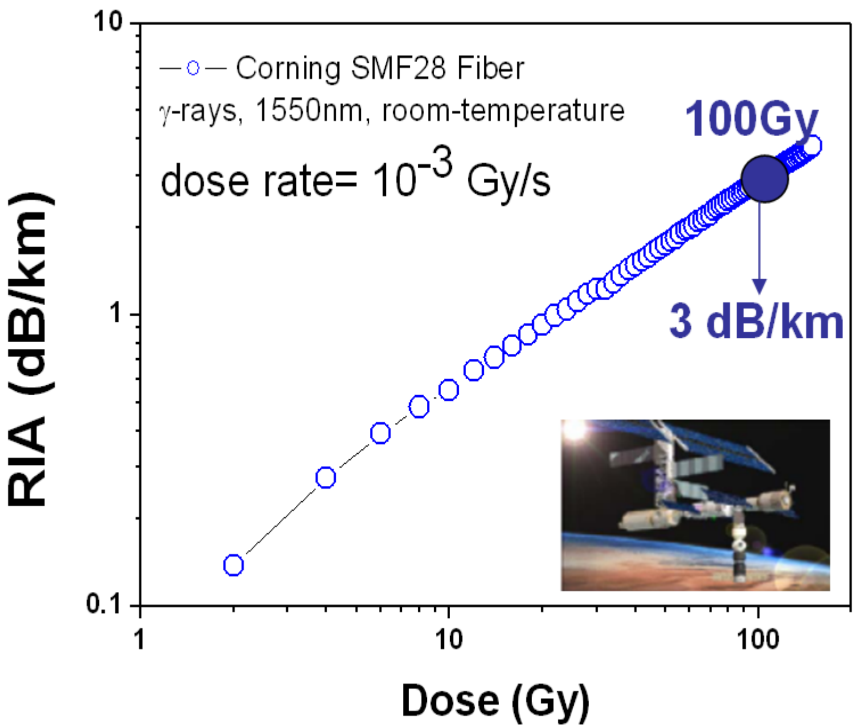
Numerous parameters, intrinsic or extrinsic to the fiber influence its radiation response

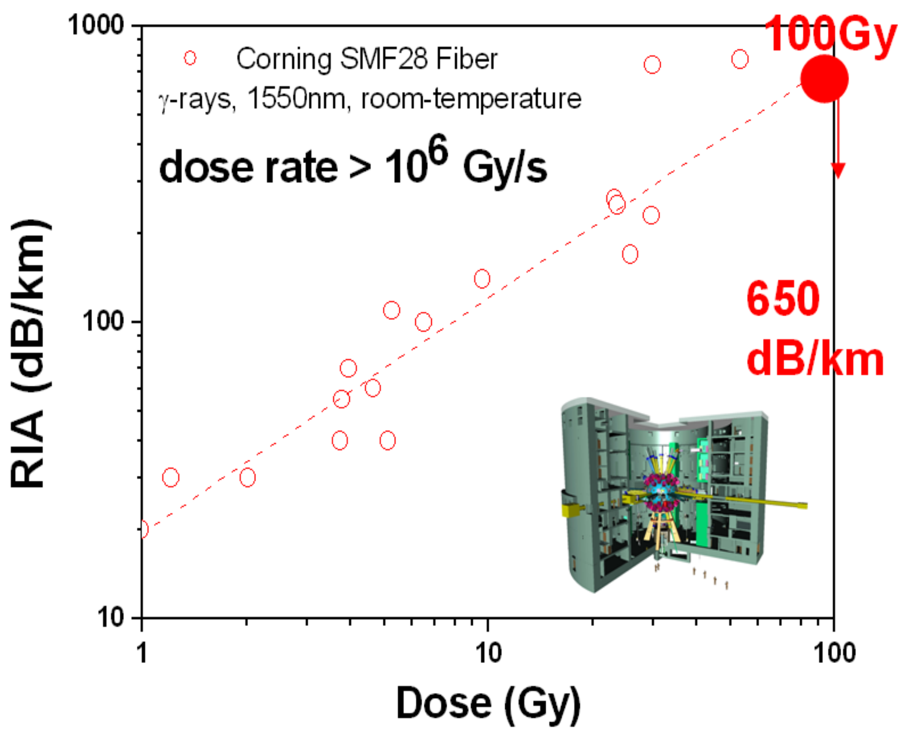


- These parameters affect the radiation-induced attenuation (RIA) levels that mainly define the **fiber vulnerability** for data transport

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

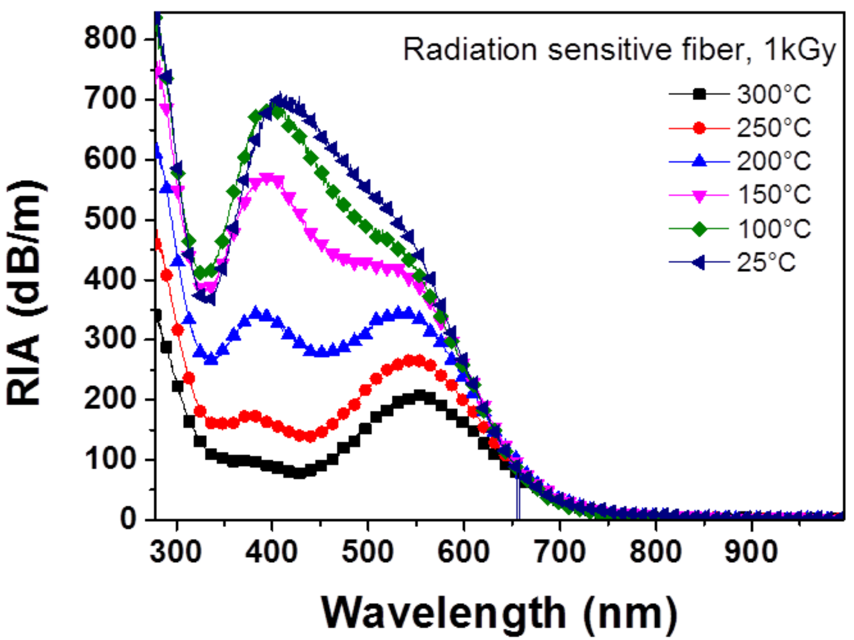
⇨ **Vulnerability ➔ the harsh environment associated with the application ➔ COTS Rad Hard Fibers?**

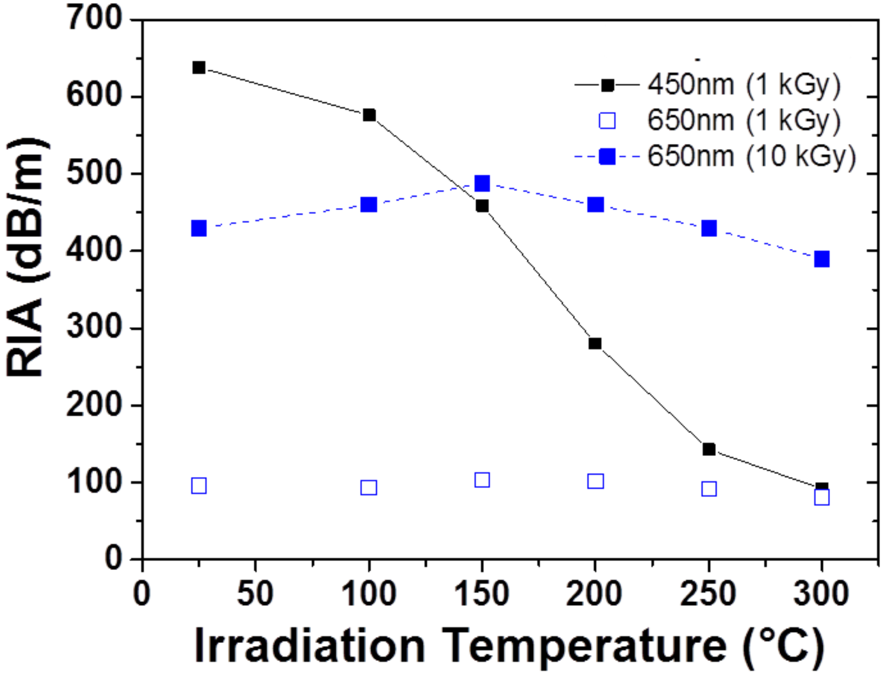




$$RIA = f(t, D, \dot{D}, T)$$

Fiber vulnerability: RIA levels and kinetics depends on the temperature of irradiation

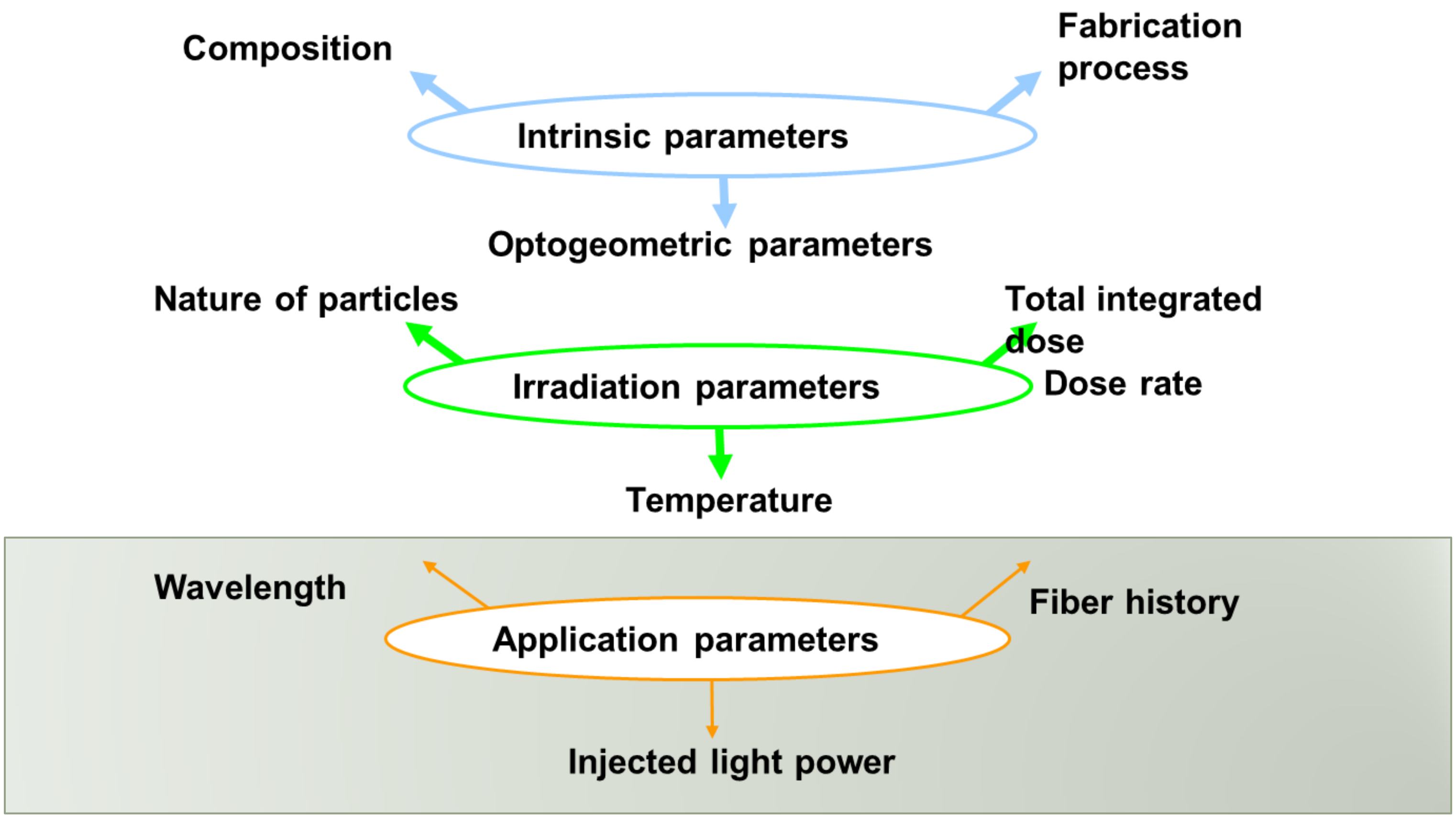




- ❑ This is a crucial parameter that has been poorly and badly studied. We showed that the usual approach combining R+T is not representative of R&T.
- ❑ Very complex leading to difficult extrapolation for future environments

S. Girard, et al., IEEE Transactions on Nuclear Science, vol.60, n°6, pp. 4305 - 4313, 2013.

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

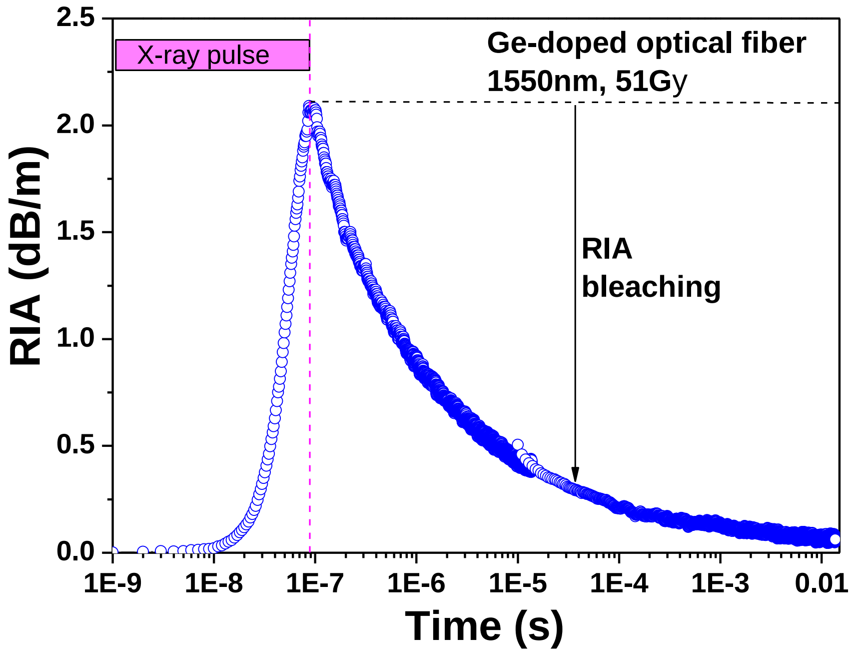


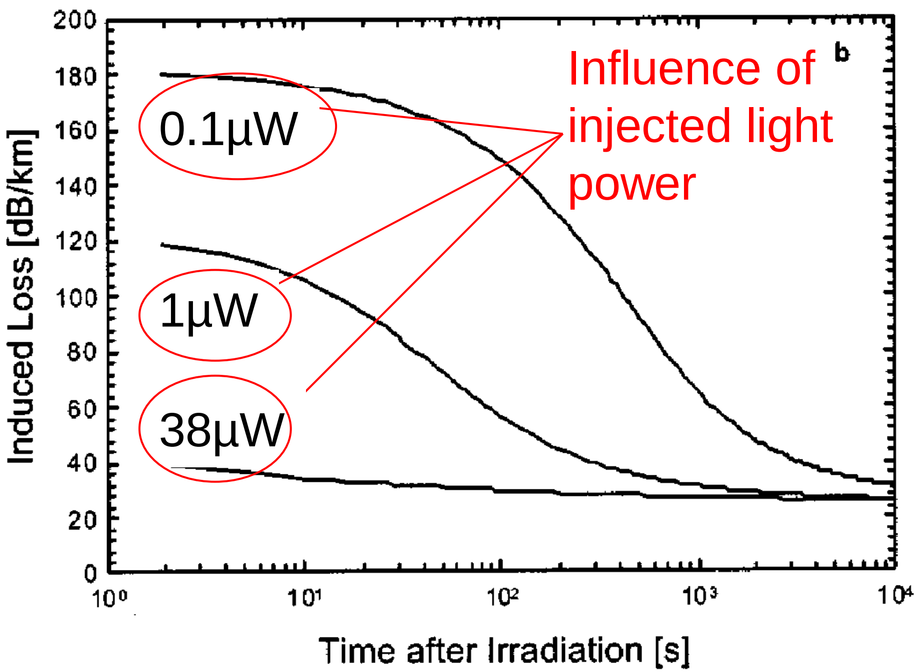
- These parameters affect the radiation-induced attenuation (RIA) levels that mainly define the **fiber vulnerability** for data transport

Fiber vulnerability: RIA 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: *wavelength and power levels of the injected signal, …*





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

- 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**

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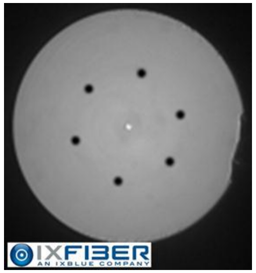
Draka

- 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 metal-coated,…) for space and nuclear industry



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

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RECENT ADVANCES ABOUT FIBER-BASED SENSING IN RADIATION ENVIRONMENT

- Fiber Bragg Gratings (strain, temperature, ….)
  cf: présentations de la session 2

DISCRETE SENSING

- Raman (T)
- Brillouin (T, strain,…)
- Rayleigh (T, strain, …)

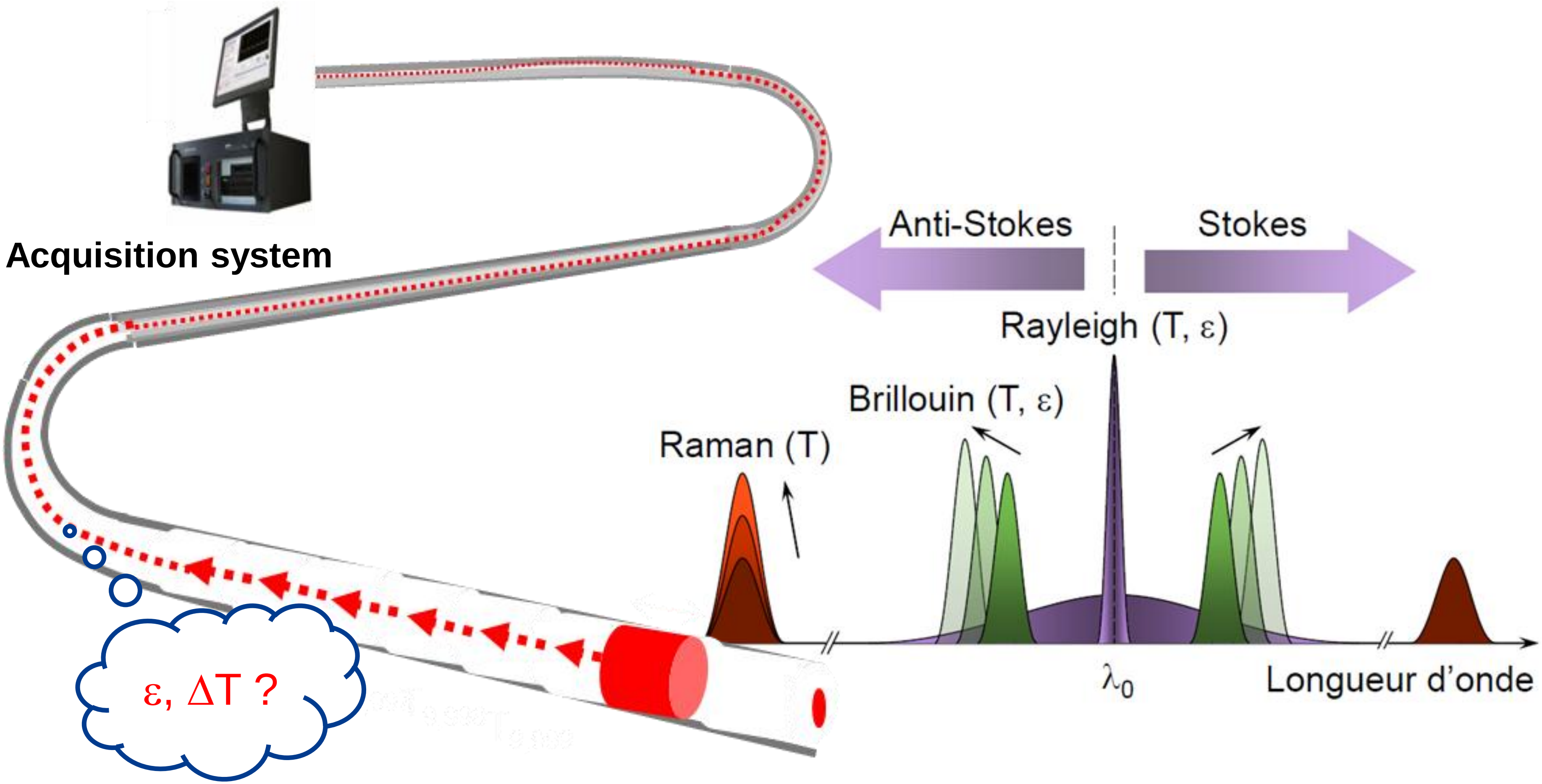
DISTRIBUTED SENSING (temperature, strain, liquid level, pressure,..)

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

PUNCTUAL, ONLINE, OFFLINE SENSING

➡ **Since Fukushima Daiichi accident, fiber-based sensors are more and more considered for integration in radiation environments**

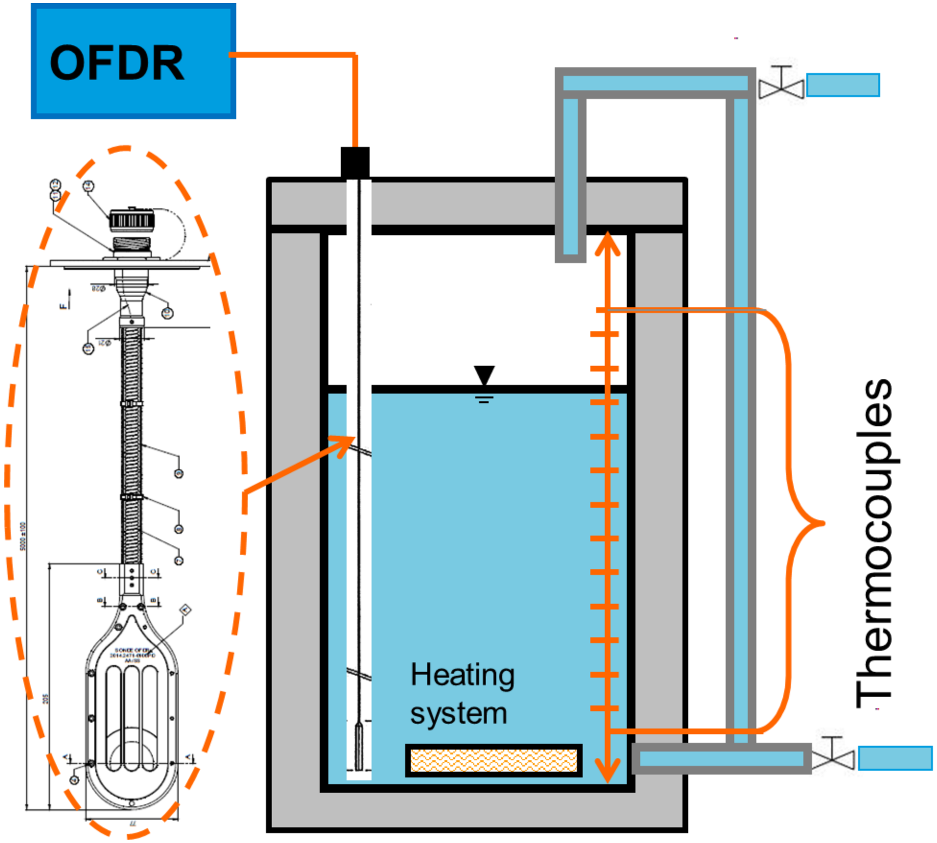
Distributed sensing based on backscattered light into an OF



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

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
- ❑ **Only RIA limits the fiber sensing range**



⇨ **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, 2015.
AREVA – LabHC, 2015 pending patents

- Fiber Bragg Gratings (strain, temperature, ….)

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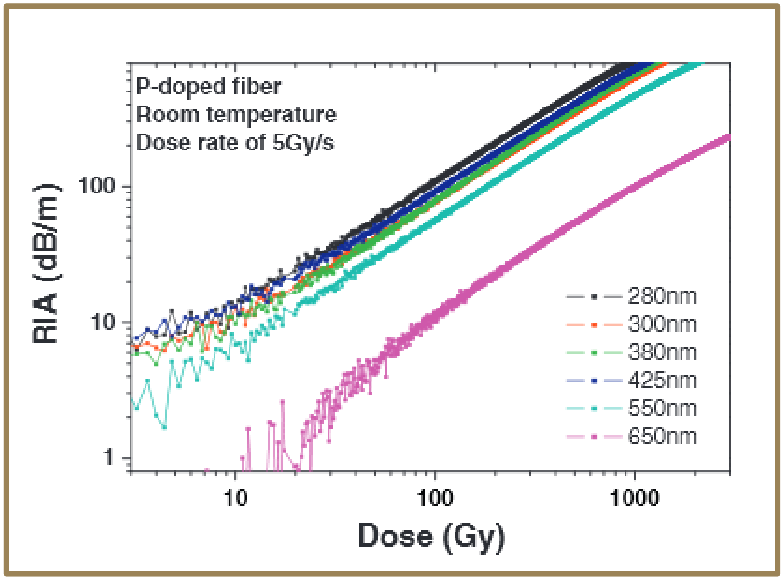
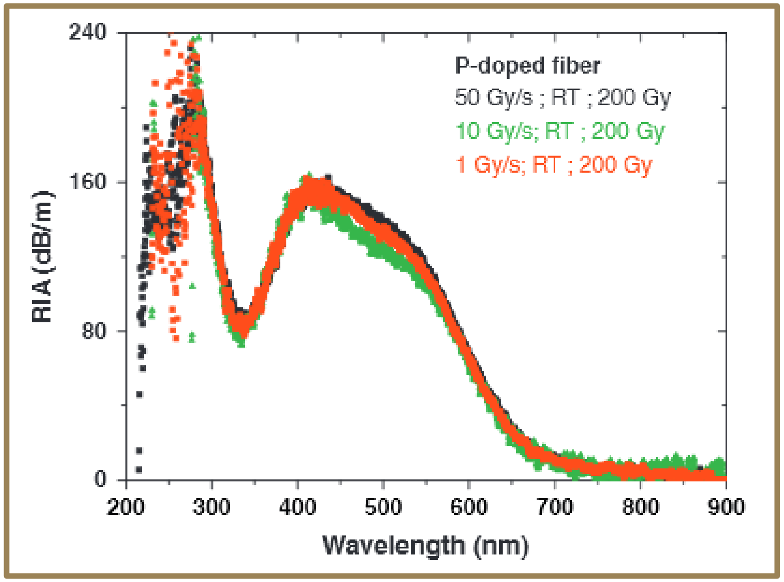
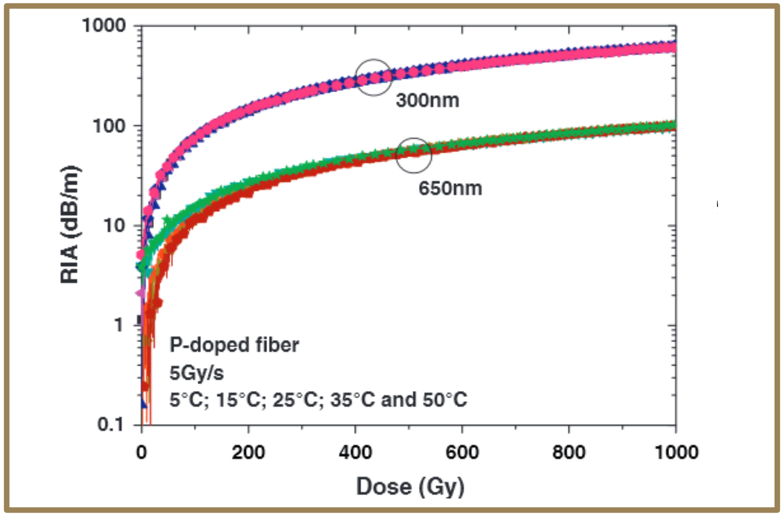
PUNCTUAL, ONLINE, OFFLINE SENSING

➡ **Since Fukushima Daiichi accident, fiber-based sensors are more and more considered for integration in radiation environments**

- 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>**







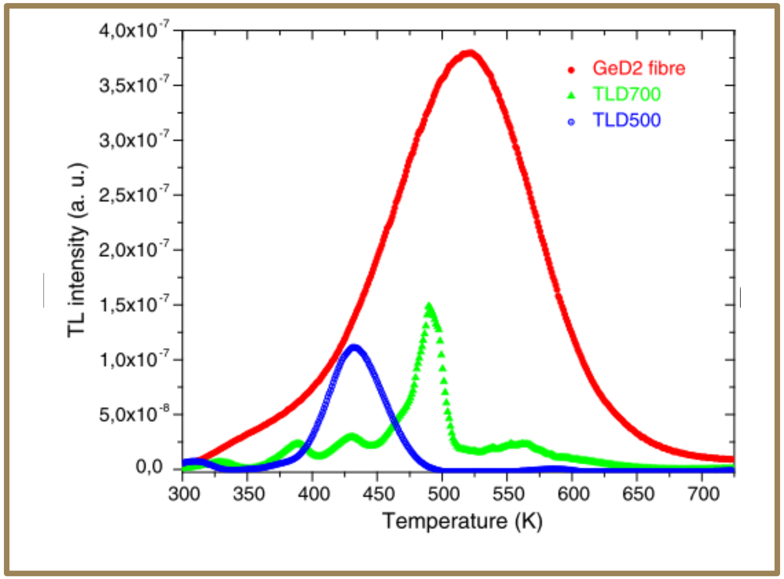
Remaining issues for fission/fusion facilities:

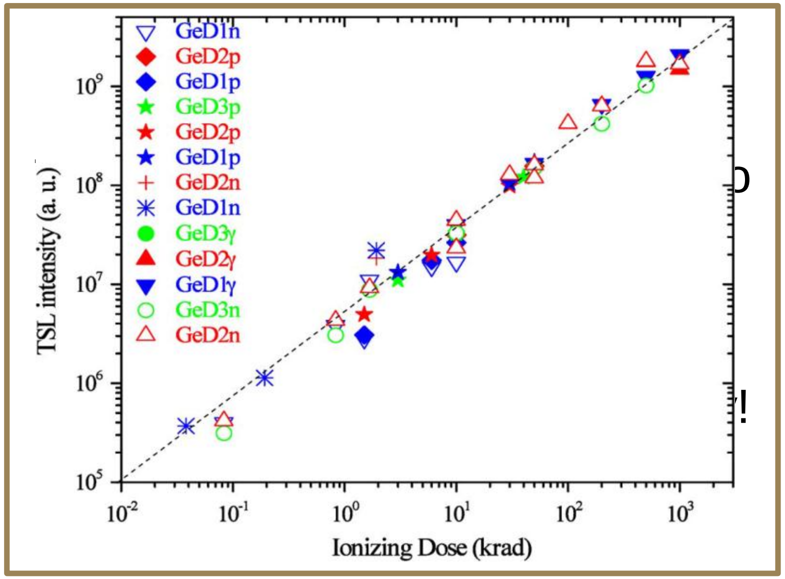
- Saturation at TID> 50kGy
- Reset of the dosimeter?
- …

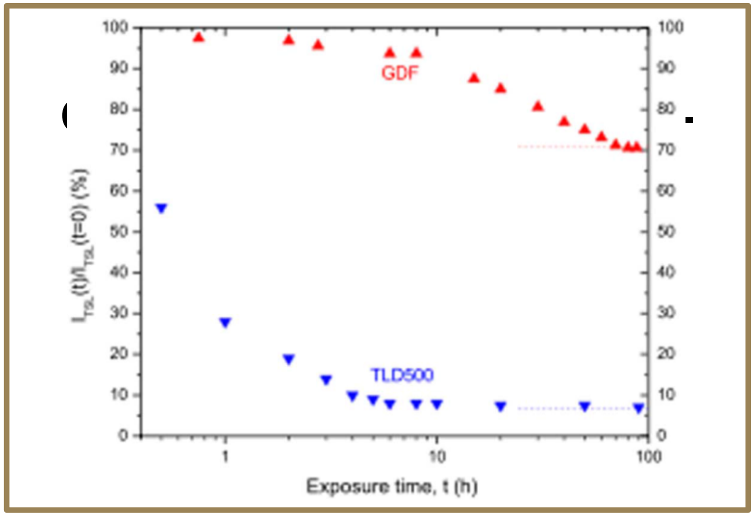
S. Girard, et al., JNCS, vol. 357(8-9), pp. 1871-1874, 2011.

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







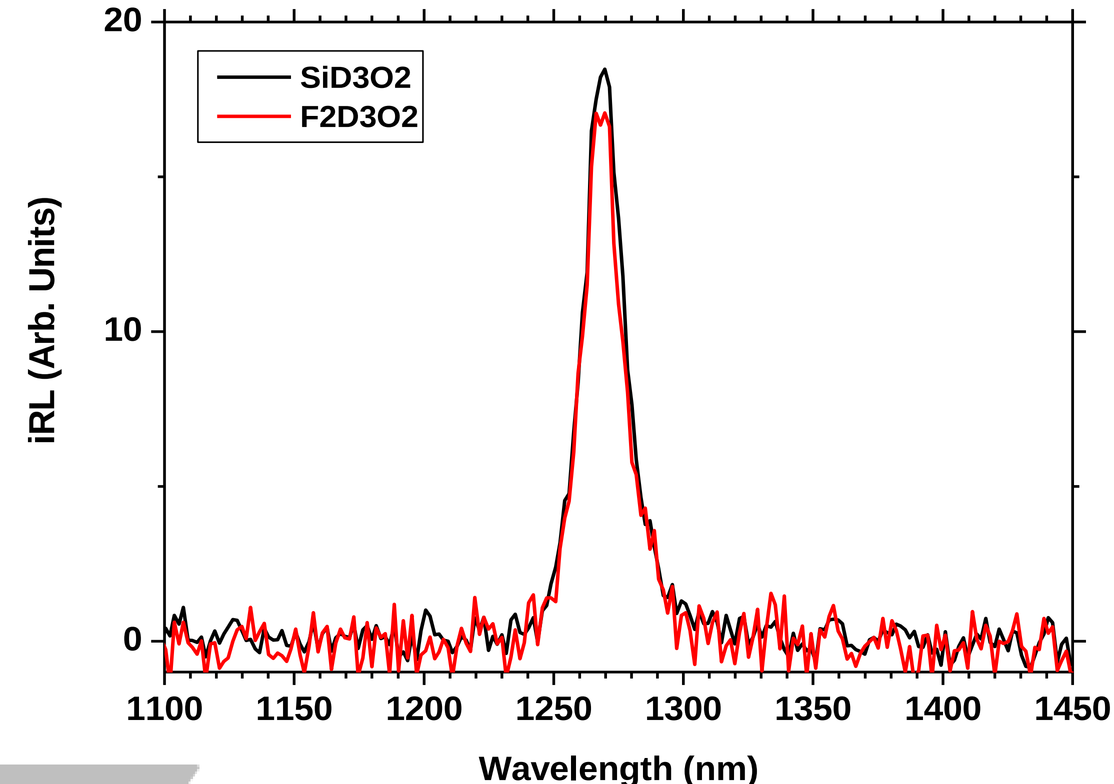
Possible applications:

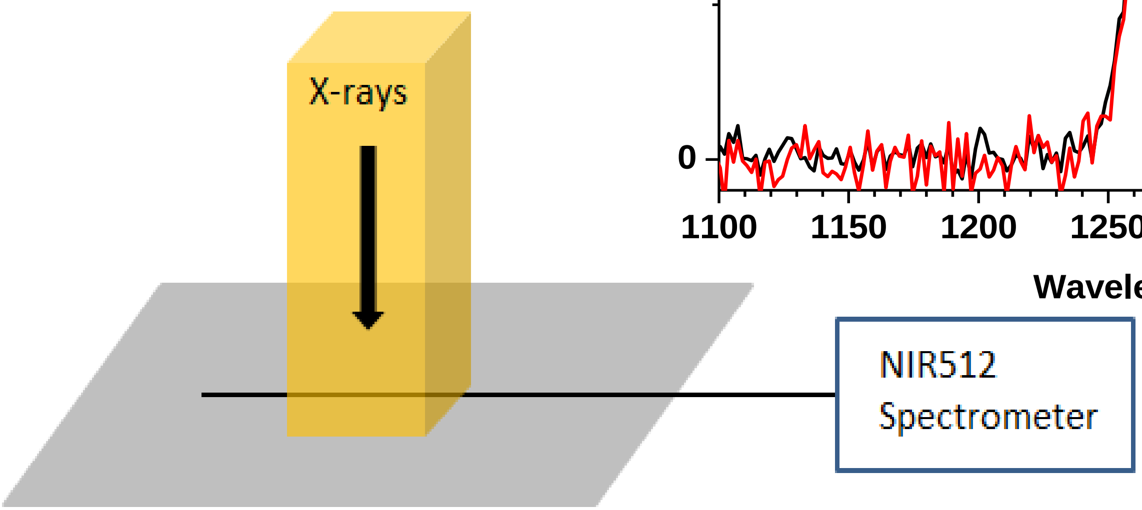
- Medical applications
- High energy physics faciilties
- …

Perspectives:

- OSL for online TID measures?

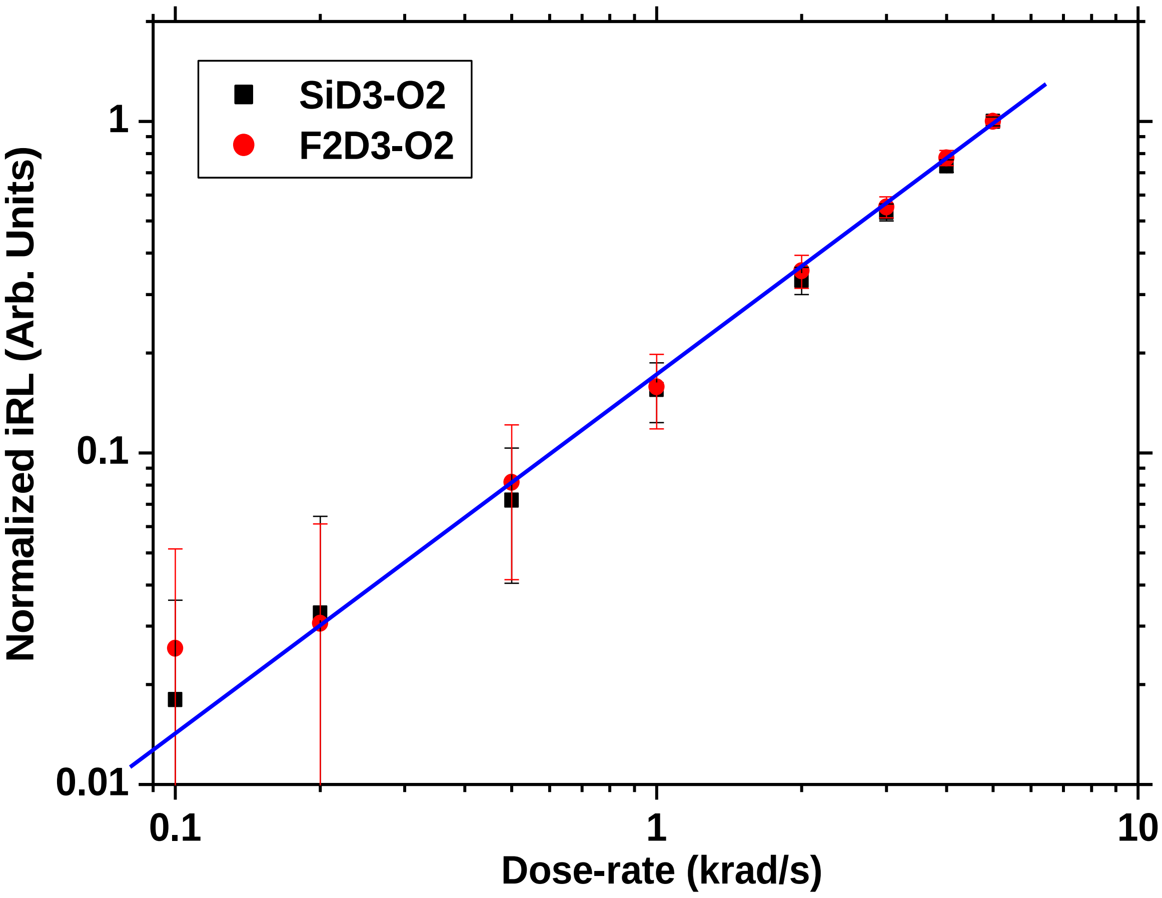
O_2 loading treatment → potentially exploitable for dosimetry applications: infrared radioluminescence (iRL)





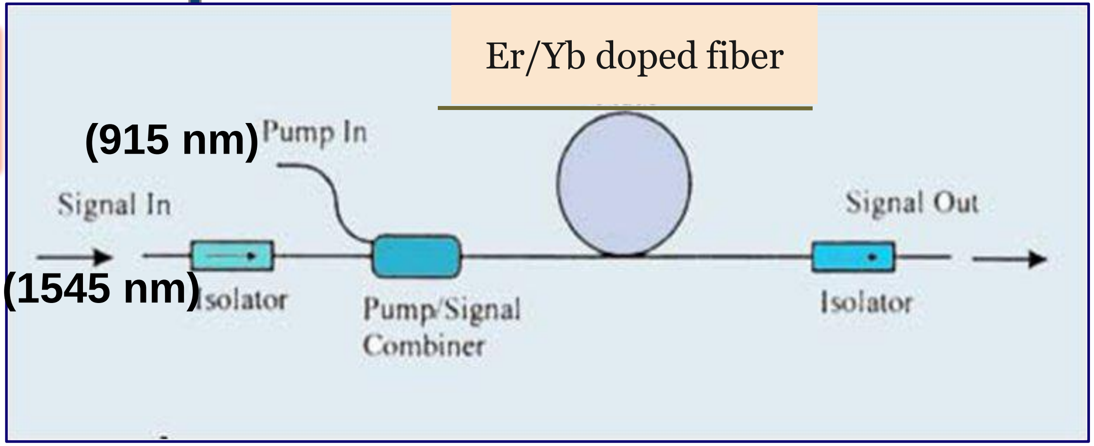
X-ray irradiation of 2.5 cm of O_2 loaded OF.

iRL depends linearly on the dose rate: real time monitoring of the irradiation flux

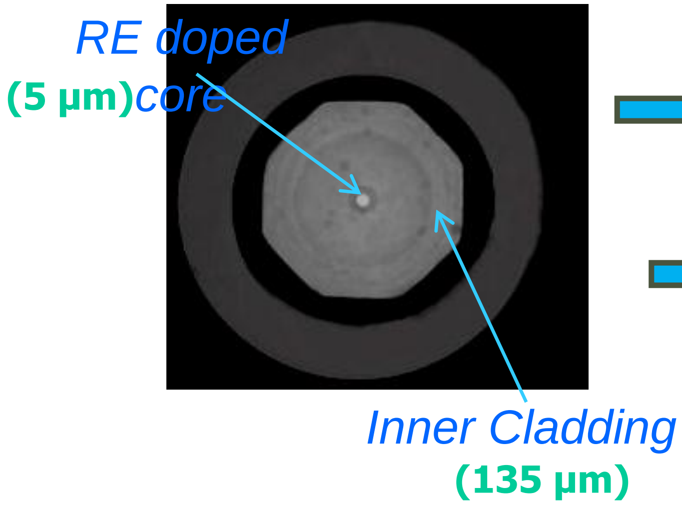


Radiation Hardening of Rare-Earth Doped Fiber Amplifiers

Schematic setup of an EYDFA



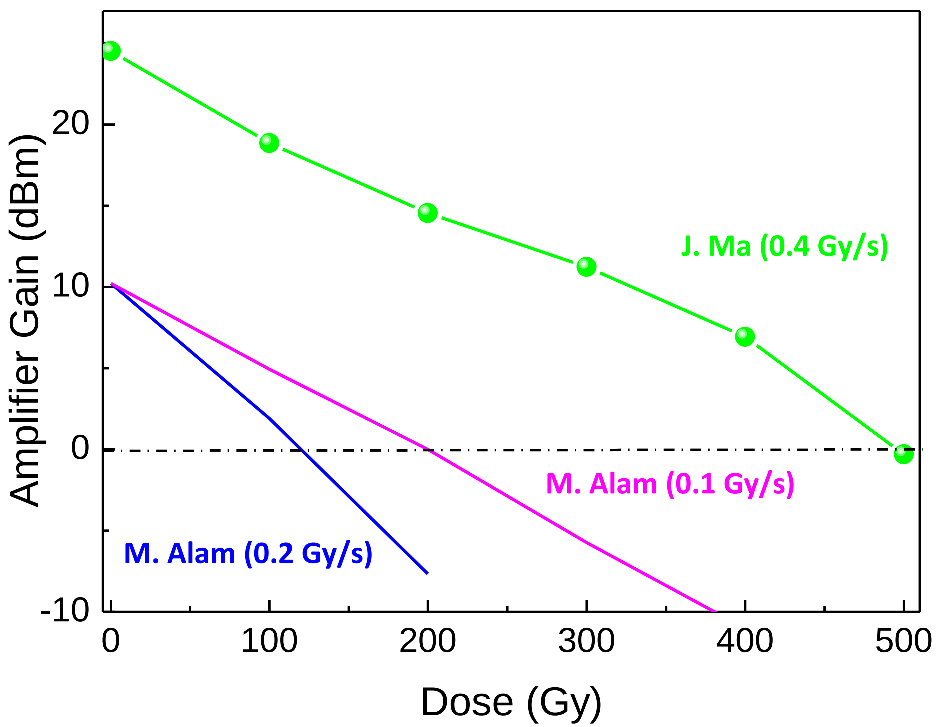
Fiber cross section



Pump propagation in the inner cladding ***(pure silica)***.

Signal propagation in the core ***(RE-co-doped phosphosilicate glass)***.

Few experiments characterizing EYDFA have been published.
Just some are performed *in active configuration*

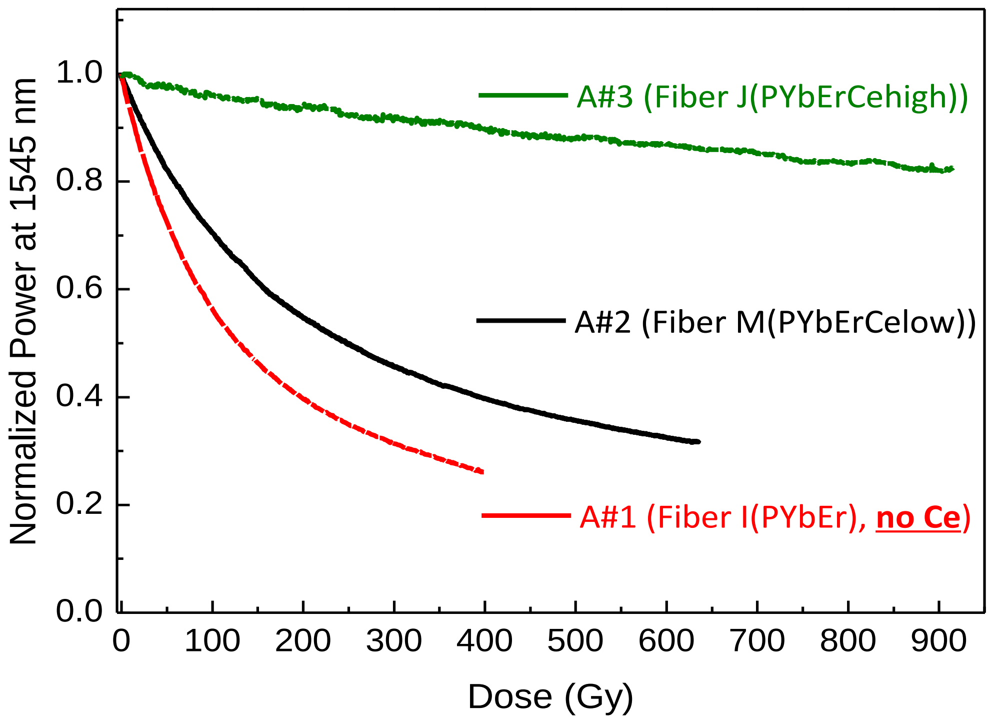


No Amplification (amplifier gain = 0) already at 120, 240 or 500 Gy.

Absorption losses increase with increasing total accumulated dose

Active characterizations in amplifier configuration

Influence of Ce do-doping



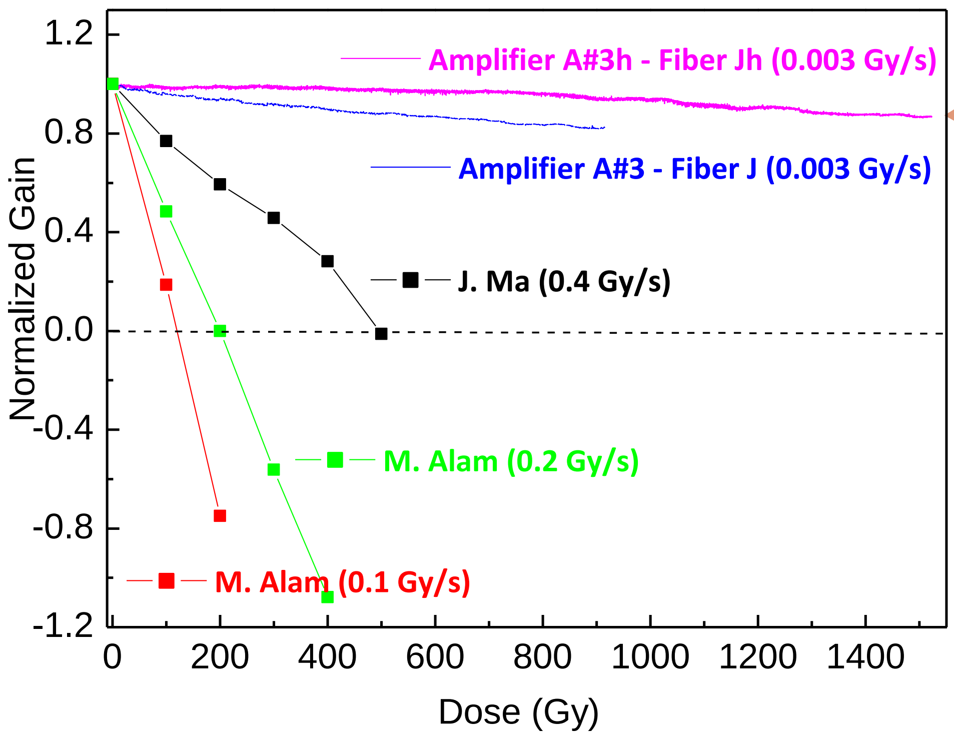
Fiber I → degradation ~3 times higher than *fiber J* (at 400 Gy).

Fiber M → slightly improved, highlighting
a proportional dependence of the hardness of the Ce-content.

Fiber J → degradation at 900Gy of ~15%

Comparison with the current state-of-art results

Ce-codoped and H_2-loaded active optical fiber



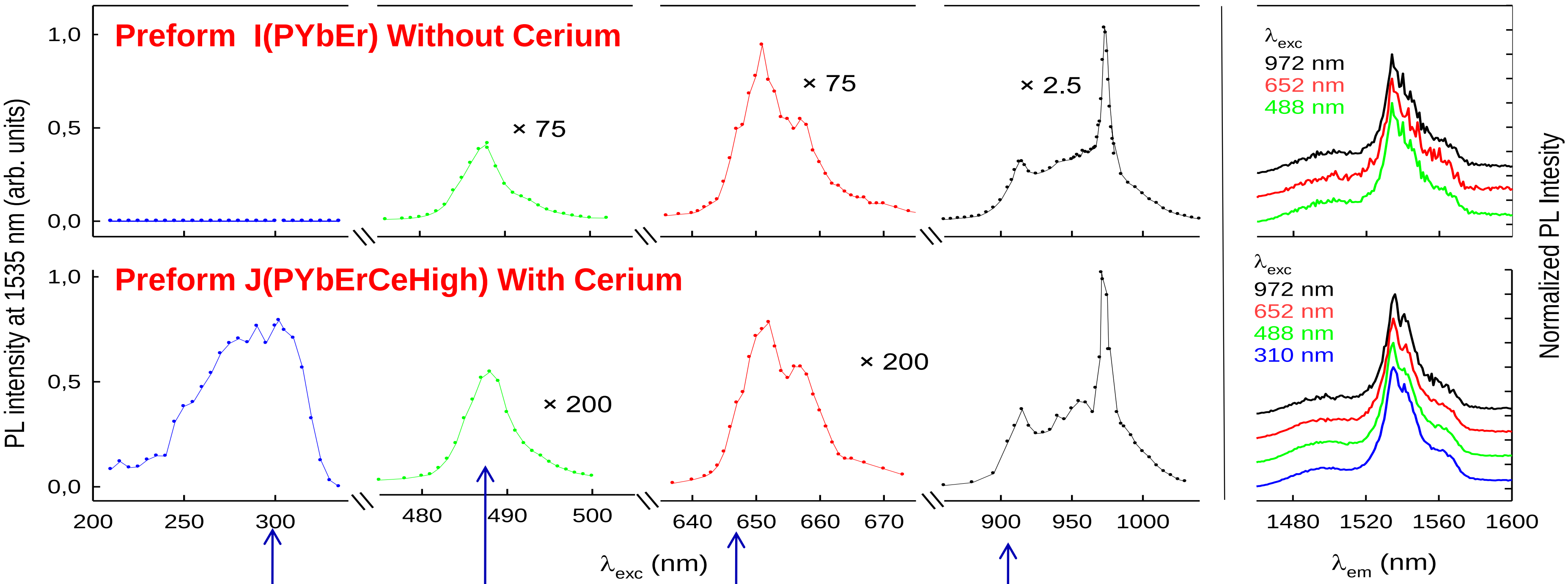
Comparison allowed even with these different testing dose-rates

host glass matrix contribution:

P-related defects independent from dose-rate

RE-presence contribution: Enhanced low-dose rate sensitivity

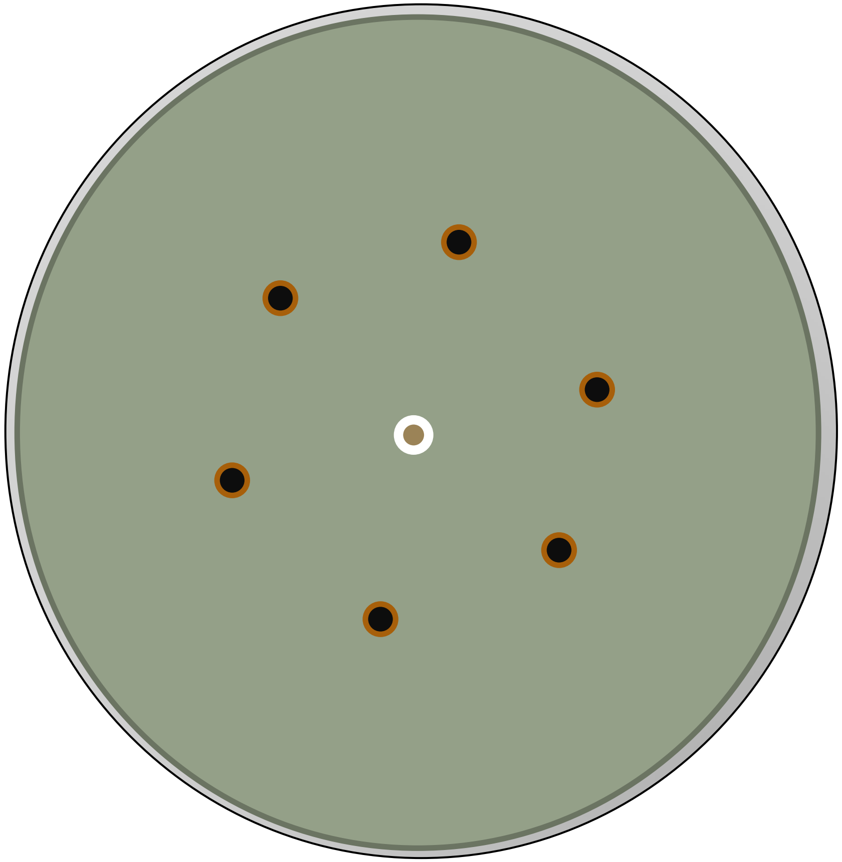
PLE spectroscopy on fiber preforms



Ce^{3+} activity Er^{3+} activity Er^{3+} activity Yb^{3+} activity

These excitation bands generate → the same Er^{3+} IR emission.

Hole-Assisted Carbon Coated Fibers: this new structure solves all the hardening issues related to radiation-hardening of EDFAs



1. The core and cladding **composition is optimized** to reduce radiation sensitivity.

2. **Holes are created at the preform manufacturing stage**. Neither hole diameter size nor number play a critical role.

3. A hermetic **carbon coating** is then deposited.

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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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- **Sylvain Girard**, PR
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- **Antonino Alessi**, Post-Doc, UJM / Basics of radiation effects
- **Imène Reghioua**, PhD, UJM/ Basics of radiation effects / point defects
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- **Chiara Cangialosi**, PhD ANDRA, Fiber sensing (Brillouin, Raman)
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- **Thomas Blanchet**, *PhD CEA DRT, Basics of neutron induced effects*
- **Blaz Winkler,** *PhD Nova Gorica, Ab initio simulation of point defects*

Merci pour votre attention…