LABORATOIRE HUBERT CURIEN
UMR • CNRS • 5516 • SAINT-ETIENNE

Recent vulnerability and hardening studies of optical systems, fibers and fiber sensors at high radiation doses

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Final Presentation Days

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Outline

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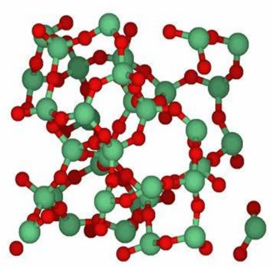
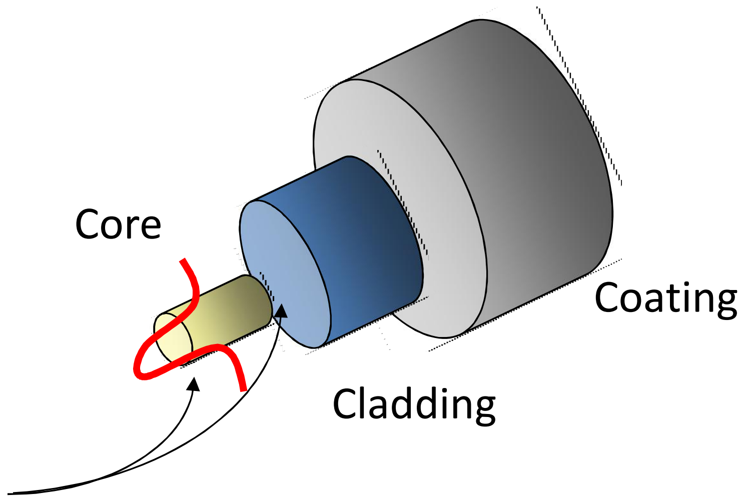
- **Introduction:** Context
- **Part 1:** Basic mechanisms of radiation effects on optical fibers
- **Part 2:** Recent achievements on radiation hardened REDFA for space missions
- **Part 3:** Recent Advances on Optical Fiber Sensing in Harsh Environments

Review paper: S. Girard, J. Kuhnhenn, A. Gusarov, B. Brichard, M. Van Uffelen, Y. Ouerdane, A. Boukenter, and C. Marcandella, "*Radiation Effects on Silica-based Optical Fibers: Recent Advances and Future Challenges*", IEEE TNS, **60** (3) 2015 - 2036, 2013

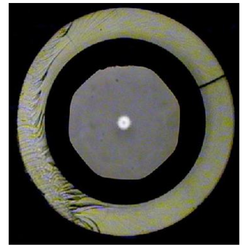
Silica-based optical fibers are widely used in radiation environments for various applications operating in the UV - IR range of wavelengths

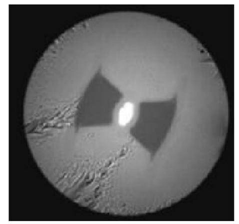


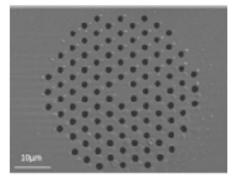
Amorphous silica

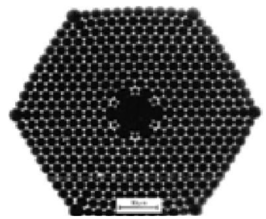


- ❑ **Data links**
- ❑ **Diagnostics**
  - *Laser*
  - *Plasma*
- ❑ **Fiber-based lasers**
- ❑ **Fiber-based amplifiers**
- ❑ **Sensing**
  - *Strain*
  - *Temperature*
  - *Dose*
  - *Gyroscopes*



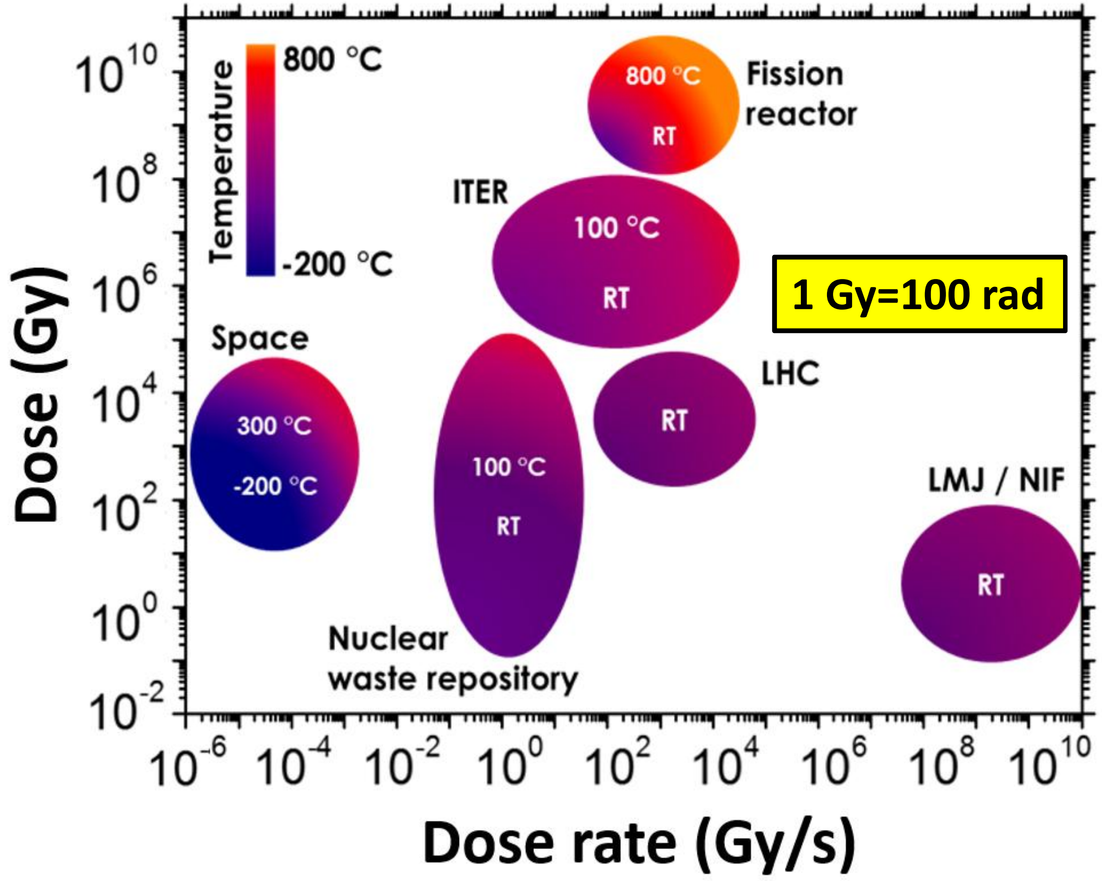






In this talk, we focus on silica-based optical fibers guiding the light by Total Internal Reflection (TIR)

Vulnerability and hardening studies of fibers and fiber-based sensors (OFS) in radiation environments



Key advantages

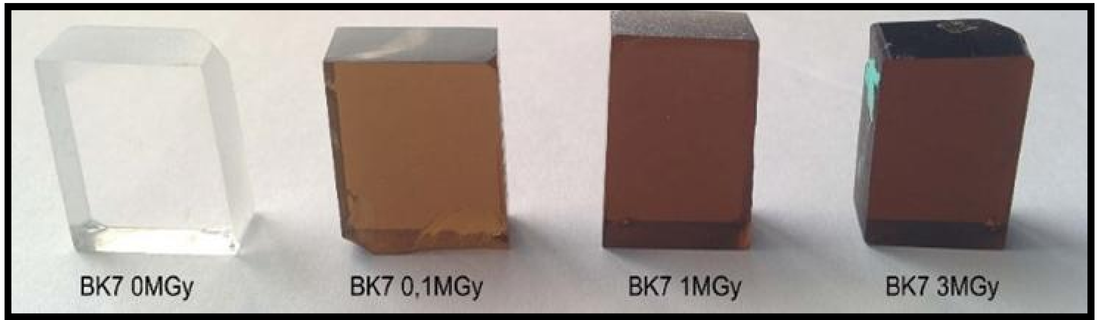
1. Electromagnetic immunity
2. High bandwidth/ multiplexing capability
3. Low attenuation
4. Low weight and volume
5. High temperature resistance

But some limitations too !

Part 1: Basic Mechanisms of Radiation Effects on Optical Fibers

Three degradation mechanisms at macroscopic scale have been identified under irradiation

1. Radiation-Induced Attenuation (RIA)

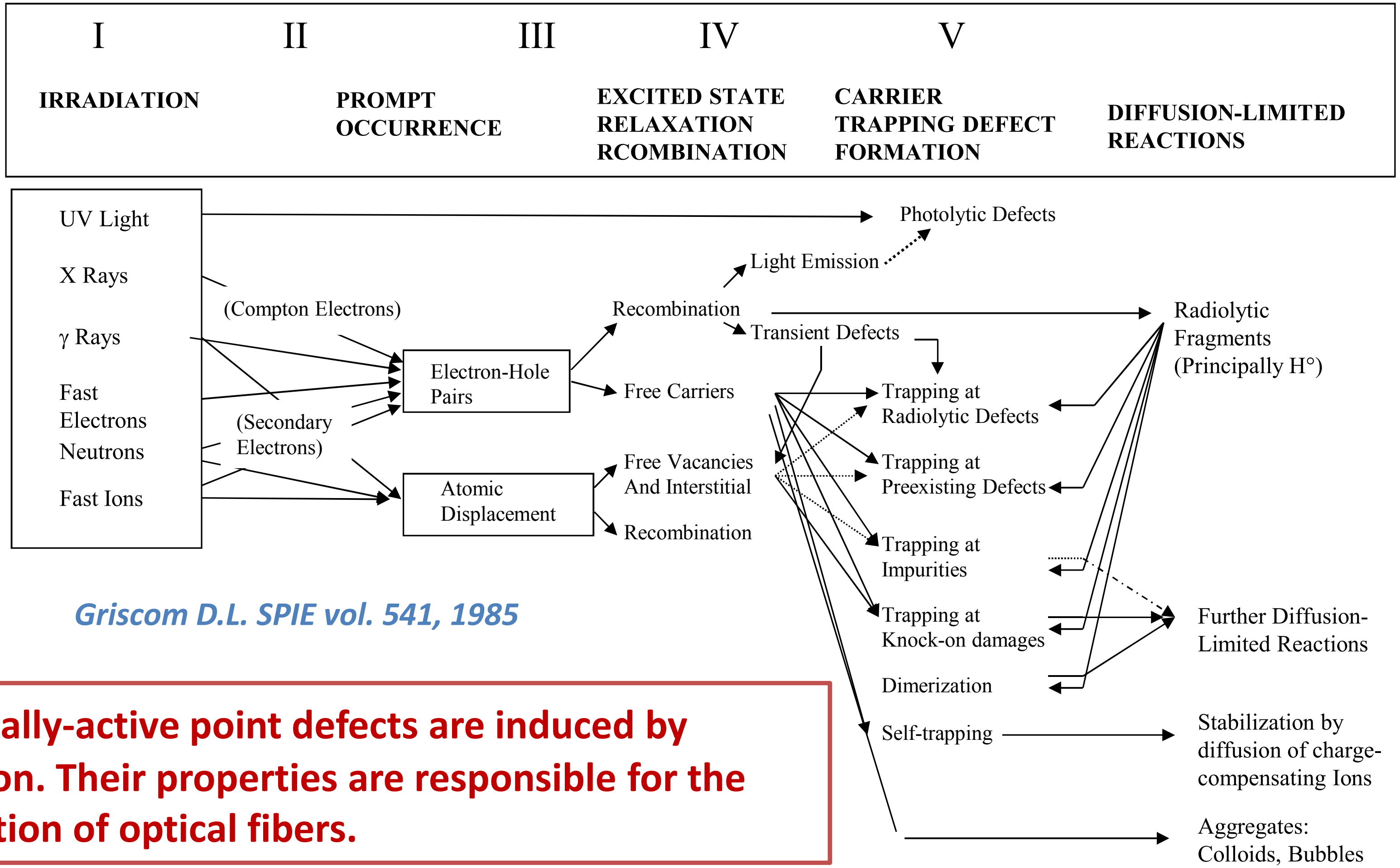


2. Radiation-Induced Emission (RIE)

3. Compaction

➢ **The relative contributions of these 3 mechanisms depend on the <u>radiation environment</u>, on the <u>targeted application</u> and <u>on the fiber properties</u>**

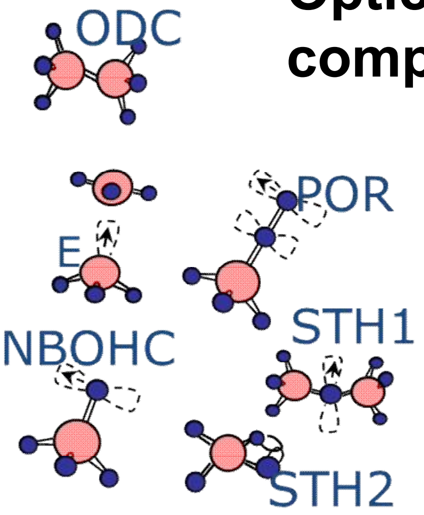
Mechanisms occurring at the microscopic scale in *a*-SiO2 are well known …

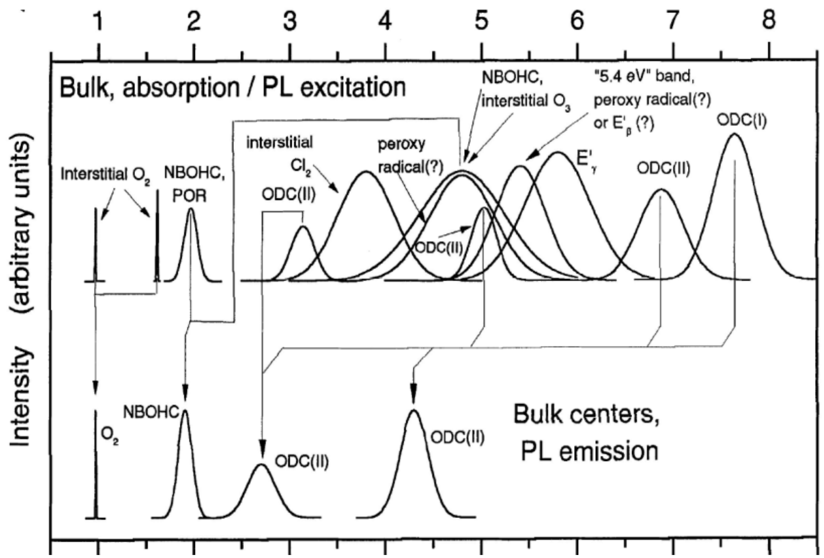


Griscom D.L. SPIE vol. 541, 1985

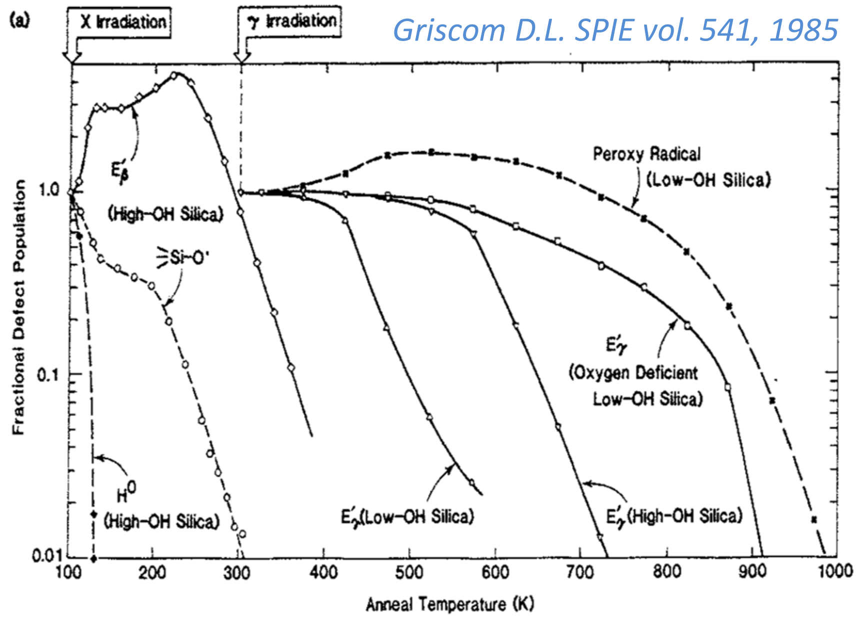
⇨ Optically-active point defects are induced by irradiation. Their properties are responsible for the degradation of optical fibers.

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





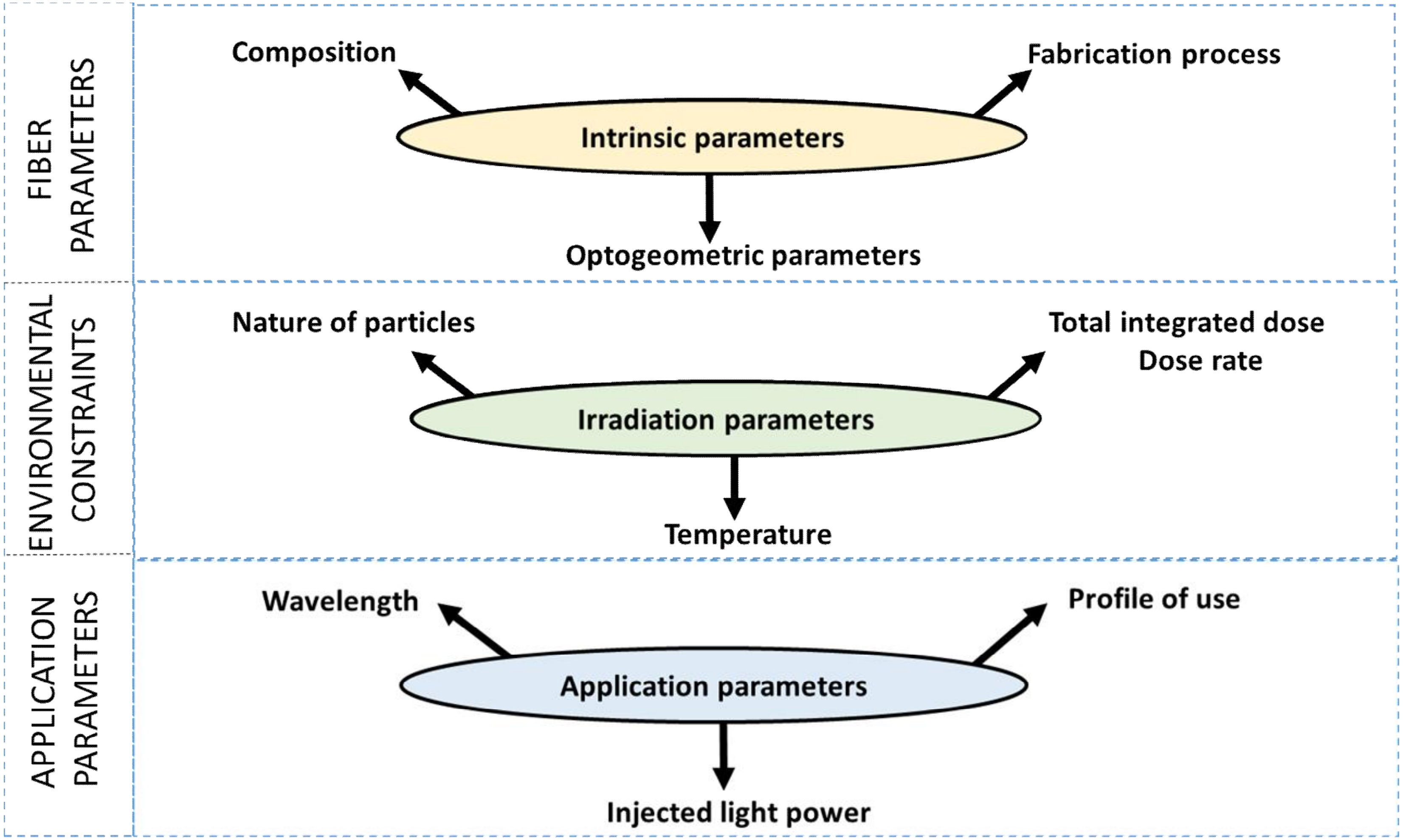
L. Skuja; NATO Book Chapter, 2000



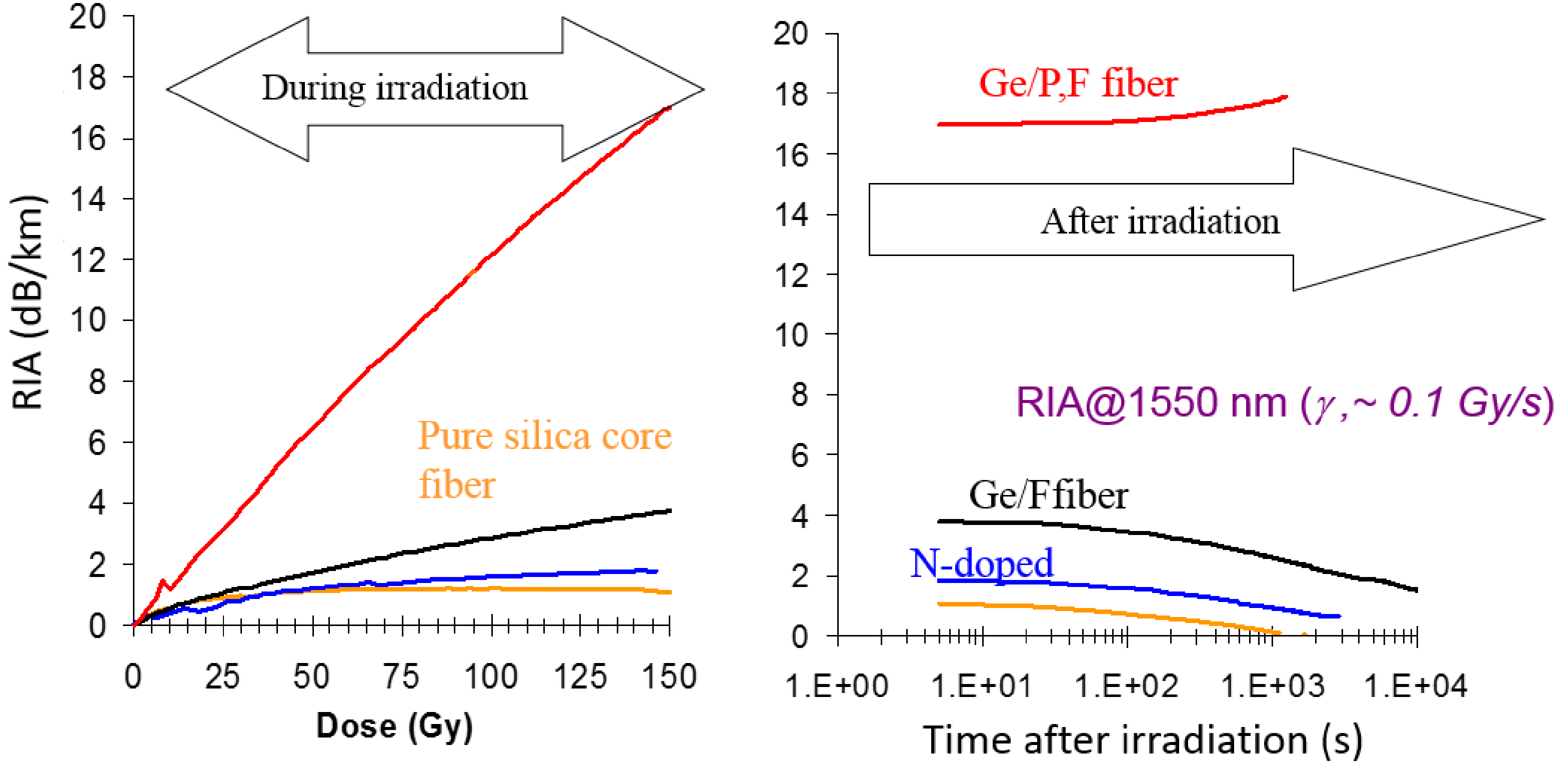
Griscom D.L. SPIE vol. 541, 1985

- ❑ Each parameter affecting the properties of these point defects will impact the OF response.
- ➢ Too complex to be yet predictable! ➔ **radiation tests on fibers are mandatory before integration (when possible)**

Numerous parameters, intrinsic or extrinsic, influence the RIA levels and kinetics



Fiber sensitivity strongly depends on its composition: core dopants

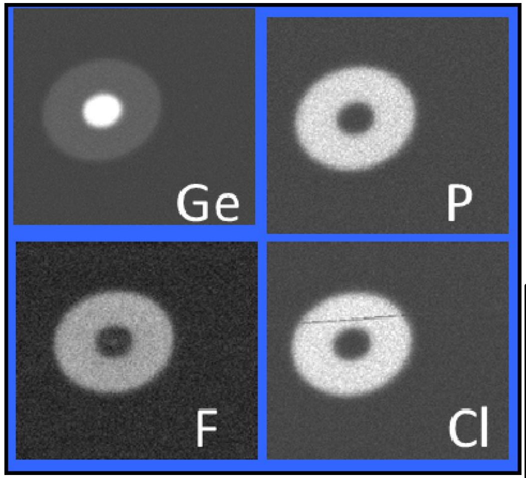


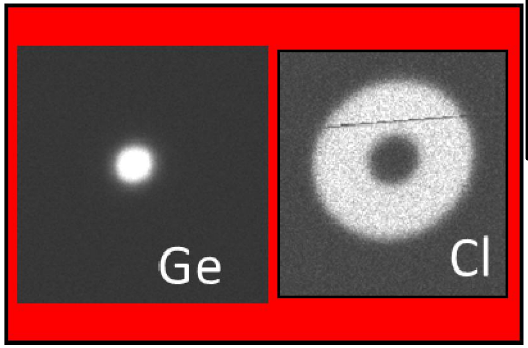
S. Girard et al., NIMB 215: 187-195, 2004 *S. Girard et al., JLT 22(8): 1915-1922, 2004.*

➡ **<u>No ideal composition exists</u>, no optical fiber is radiation tolerant to all investigated environments**

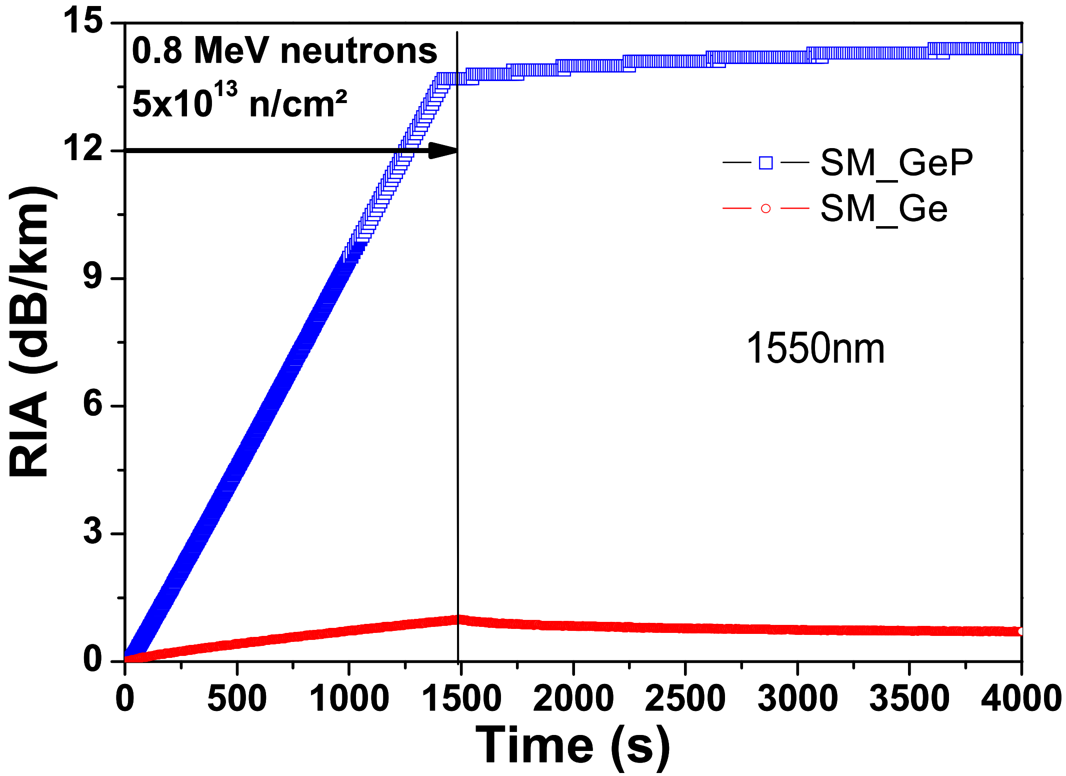
Fiber sensitivity strongly depends on the fiber composition: cladding dopants

A slight change in cladding composition strongly changes the fiber RIA levels and kinetics

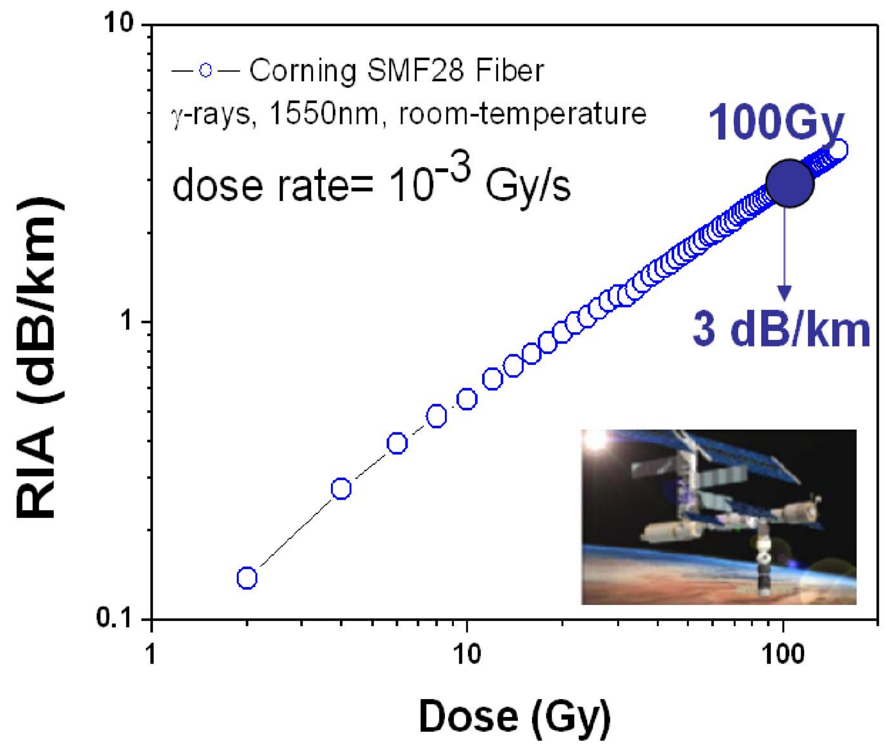


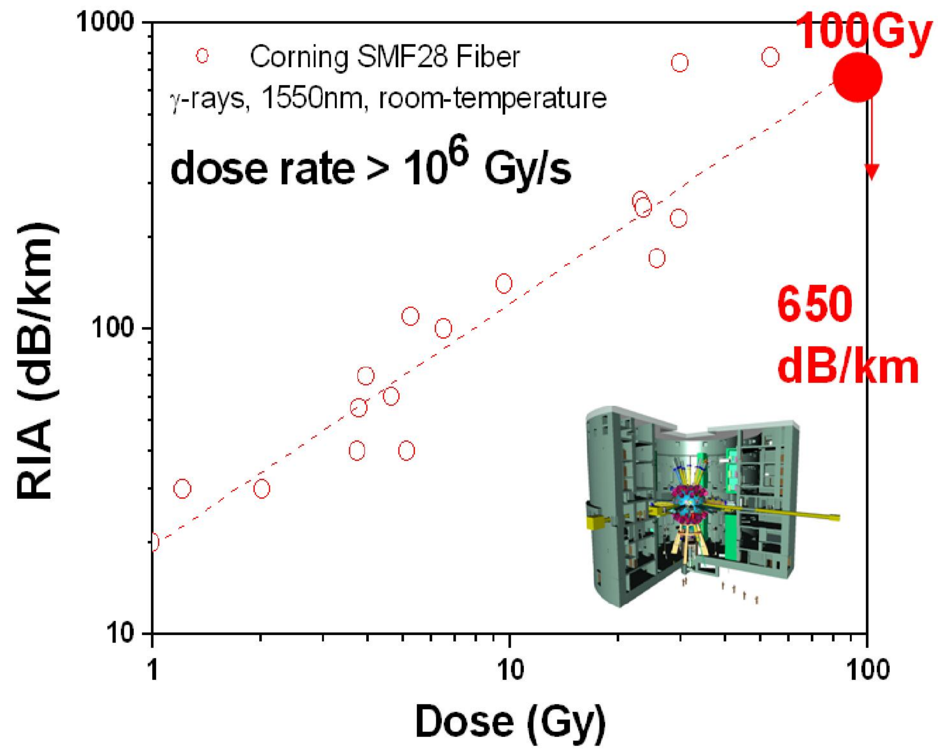


2 Telecom SMF ➔ same reference / optical performances BUT different cladding compositions



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





Vulnerability strongly depends on the harsh environment associated with the application ➔ **what means COTS Rad Hard Fibers?**

Today fiber integration: COTS radiation tolerant or hardened optical fibers are now available for some key applications/environments

- ❑ Radiation Hard Optical Fibers exist today for most of IR applications at MGy dose
- ❑ More efforts are in progress to have a **full product** (cable, connectors,…) **qualified for harsh environments**
- ❑ **CHALLENGES:**
  - ✓ Fibers for **UV operation for fusion/ fission**
  - ✓ New fiber generations (PCF, HACC, metal-coated,…)
  - ✓ **Fiber amplifiers and fiber-based lasers**

➡ **Today, functionalization of OF is targeted in order that, in addition to data transfer, they can be used to monitor environmental parameters in harsh environments**

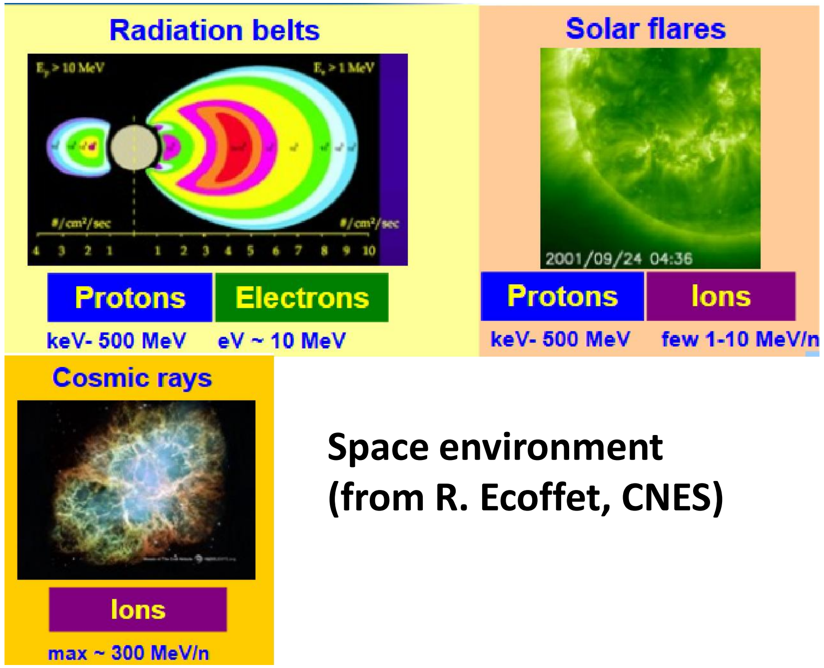
Part 2: Recent achievements on radiation hardened REDFA for space missions

Main challenge: Development of **radiation hardened Er and Er/Yb-doped amplifiers** for space missions

esa [ESA call of 2013]

- **ESA identified different types of applications such as:**

1. Loss compensation in optical x-connect for microwave photonic repeaters
2. Boosting photonics local oscillators for distribution to antenna in repeaters
3. geosynchronous equatorial orbit (GEO)/gateway optical feeder link
4. Optical Image Telemetry
5. Inter satellite bidirectional links
6. *Low Earth orbit (LEO)* to ground links



Space environment (from R. Ecoffet, CNES)

LOW Power (Er-doped, <1W) and **HIGH Power (Er/Yb, > 1W)**

Rare-earth (RE) doped fibers are very radiation sensitive and mainly explain the amplifier gain degradation under irradiation

❑ On-board testing of EDFs confirm their great sensitivity to space radiations

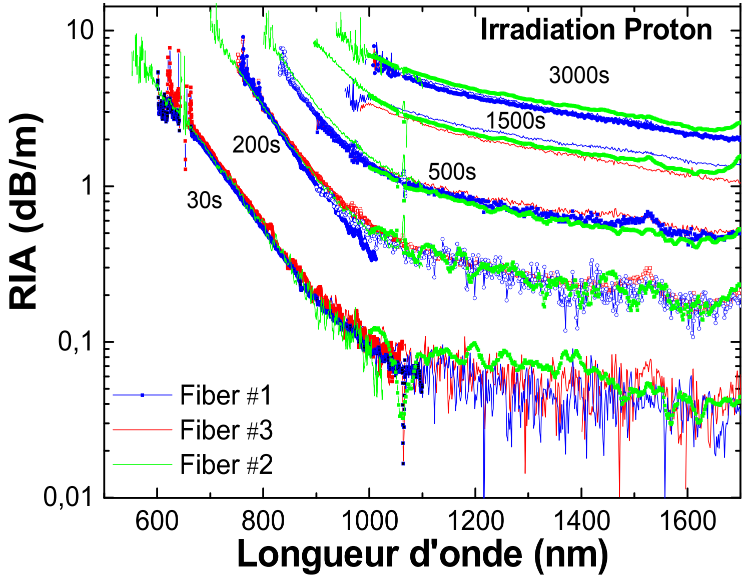
- ❑ **RE-fibers:** B. P. Fox, et al., JNCS, 378 79(2013)
- ❑ **Er-doped fs laser source:** J. Lee, et al., Nature Sci. Rep., 4 5134 (2014)

State-of-the-art in 2012

➢ **Origin of RIA:** Their host matrix is mainly responsible of RIA at the pump and signal wavelengths that causes the amplifier degradation

❑ **Different techniques have been used to improve their responses with some limitations:**

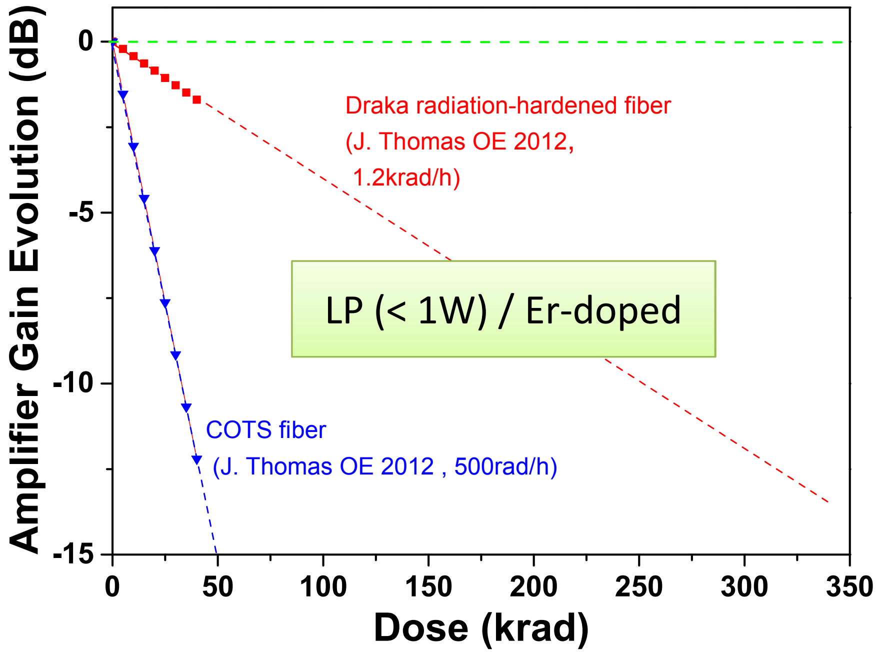
- ❑ **Nanodeposition to avoid Al in Er-doped fibers:** J. Thomas et al., Opt. Express 20 2435 (2012)
- ❑ **H_2 or D_2 Loading:** K. Zotov et al, Phot. Techn. Lett. 20(17) 1476 (2008).

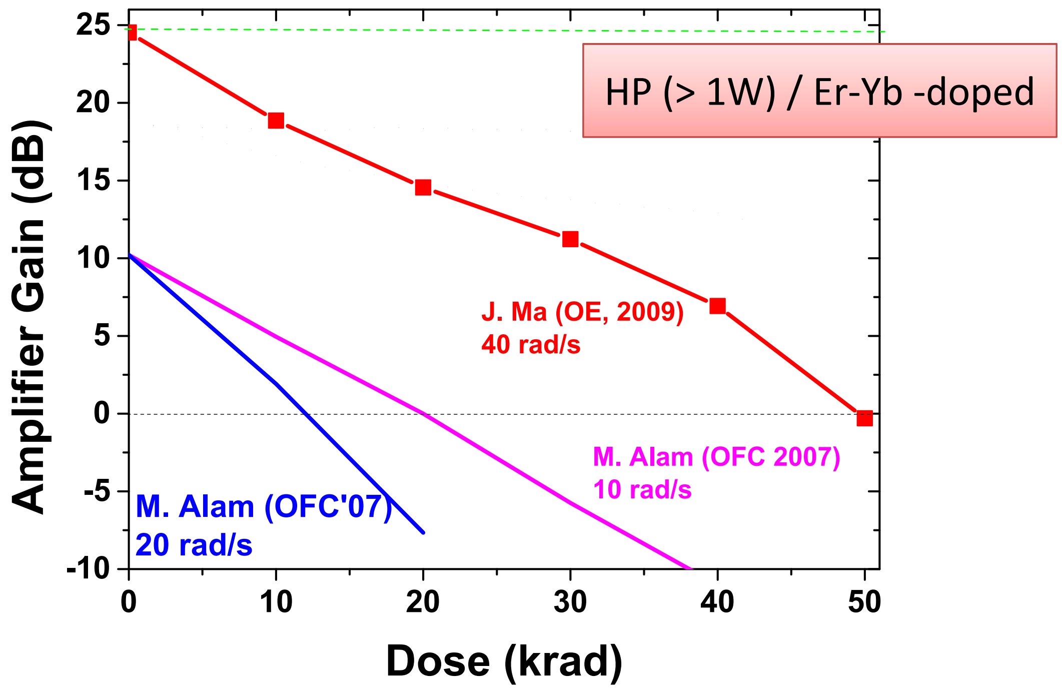


S. Girard et al. IEEE TNS, 56(6), 3293 , 2009.

State-of-the-art in 2012

❖ Both **LOW and HIGH Power** amplifiers suffer from a **quick degradation of their gain** at the low doses associated with today's space missions ➔ they cannot resist to higher doses considered for future missions





➔ Hardening by composition **(DRAKA new nanoparticles deposition process)**

➔ Screening COTS Er/Yb-doped fibers

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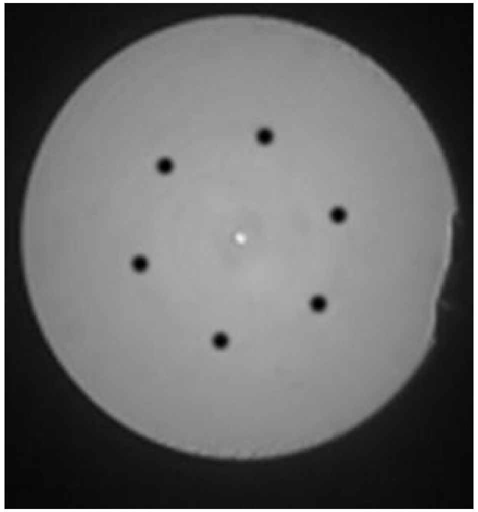
Our approach: understand the basic mechanisms of radiation effects and identify ways of mitigation (hardening by component, structure or by system)

LP (< 1W) / Er-doped

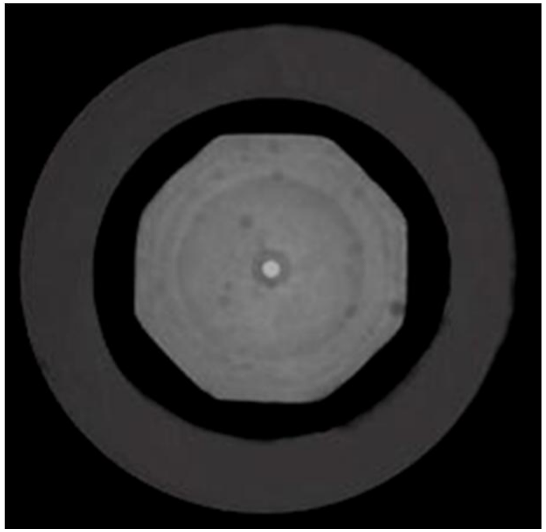
HP (> 1W) / Er-Yb -doped

- Mix of hardening-by-structure and hardening-by-component ➔ **Hole Assisted Carbon Coated (HACC) fibers**



Pending Patent n°14 50702

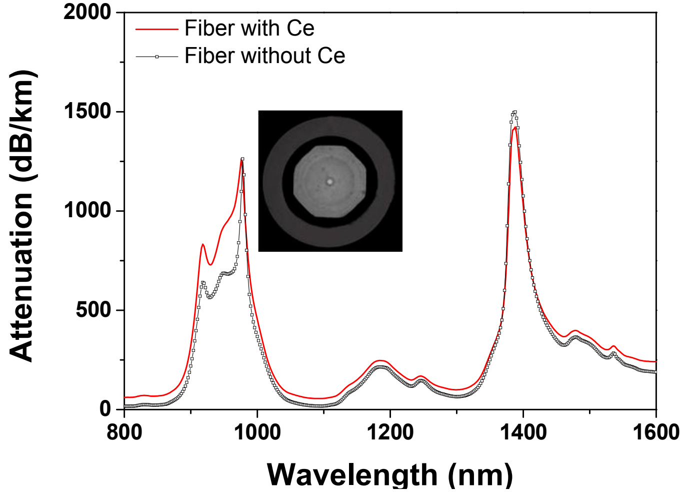
- In 2009, we suggest to use the competition between point defects to reduce fiber degradation ➔ **Hardening by Ce-codoping**



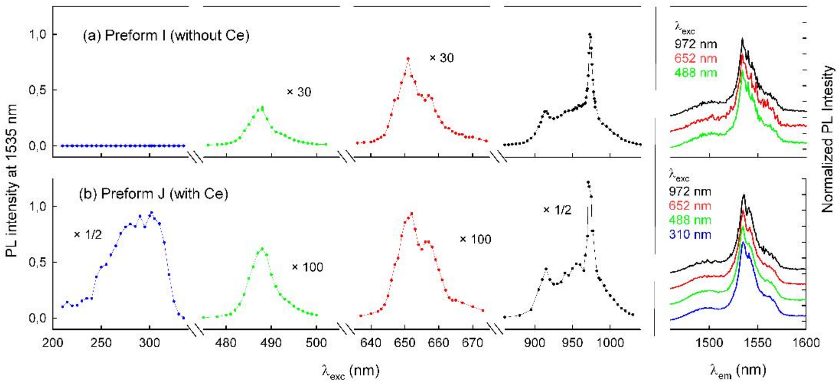
Patent: US20130101261, WO2012004547A1, EP2591387 A1

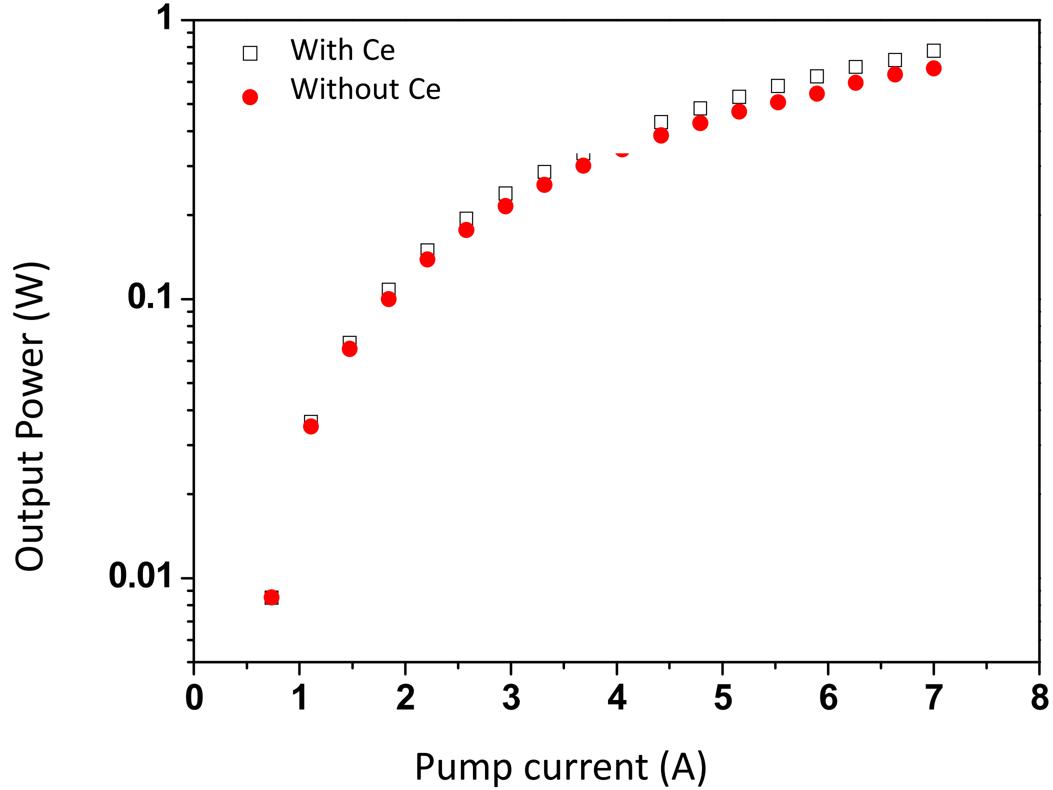
HP (> 1W) / Er-Yb -doped

Hardening by component: Cerium can be added without altering the fiber and amplifier performances



M. Vivona, *et al.*, IEEE PTL 4(6) 509 (2012)





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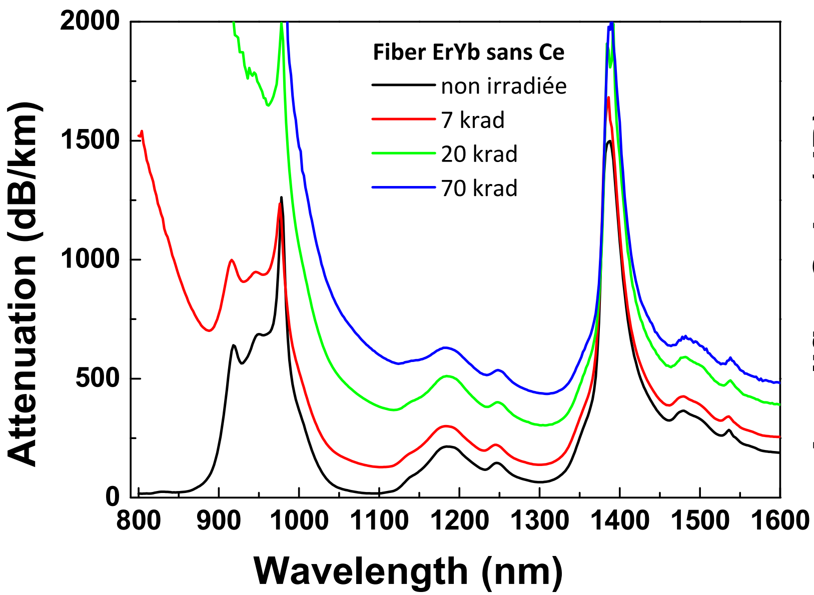
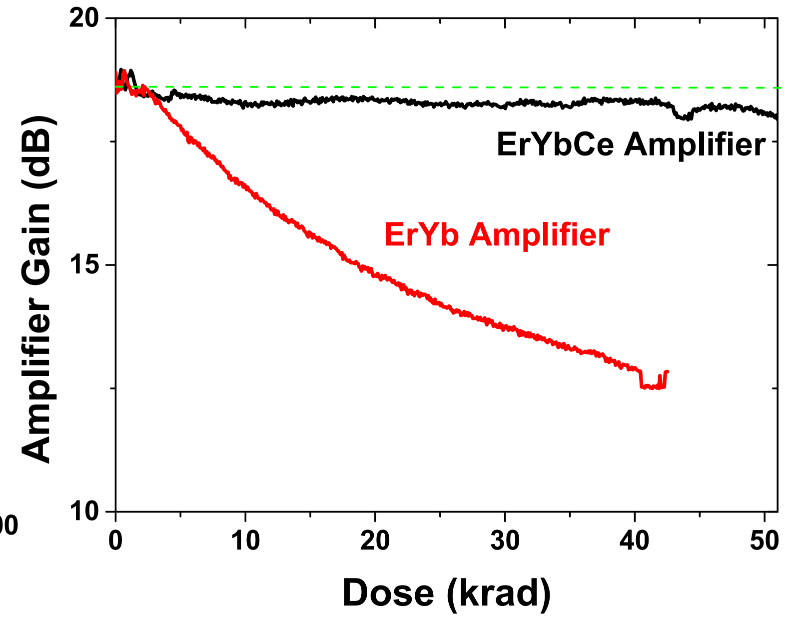
HP (> 1W) / Er-Yb -doped

Radiation tests: radiation responses of the ErYb fibers and amplifiers have been tested under X-ray, γ-ray and proton irradiations

❖ Ionisation is the main degradation mechanism and protons, X-rays and γ-rays lead to the same degradation at equivalent TIDs



Fiber response: RIA increase with dose



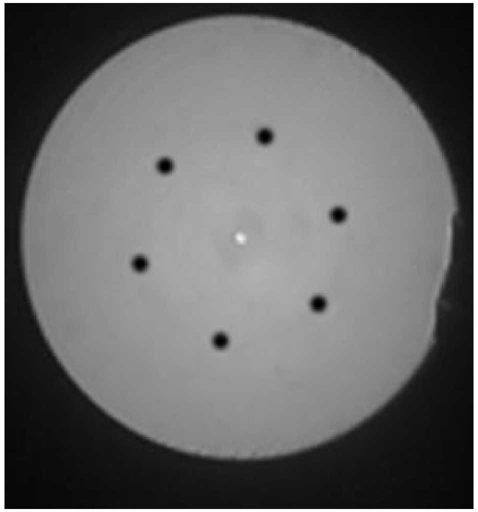
Amplifier response: gain decrease

Our approach: understand the basic mechanisms of degradation and imagine ways of mitigation (hardening by component or by system)

LP (< 1W) / Er-doped

- ❖ Mix of hardening-by-structure and hardening-by-component ➔

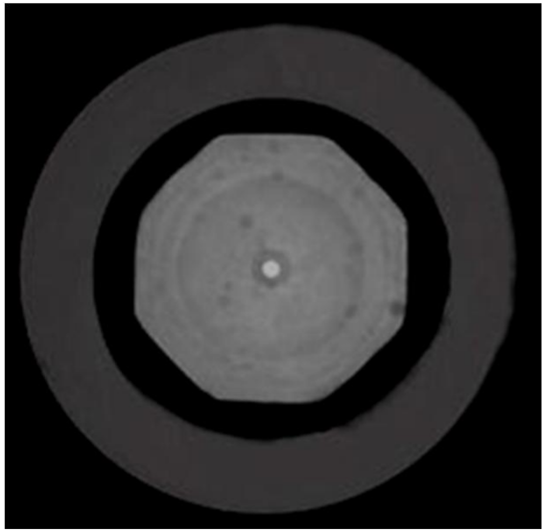
Hole Assisted Carbon Coated (HACC) fibers



Pending Patent n°14 50702

HP (> 1W) / Er-Yb -doped

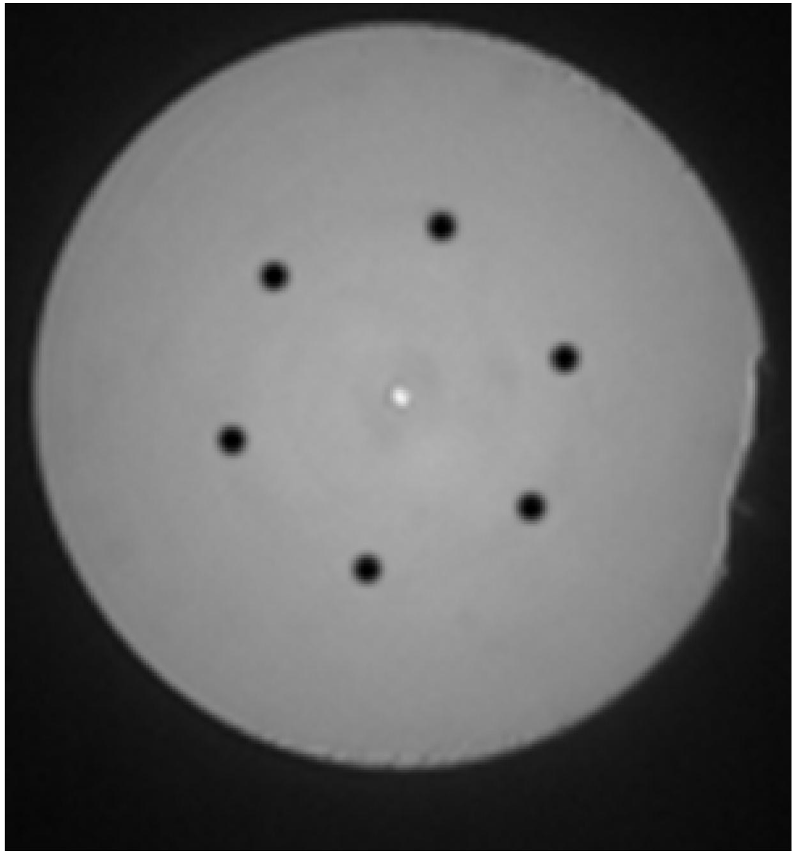
- ❖ In 2009, we suggest to use the competition between point defects to reduce fiber degradation ➔ Hardening by Ce-codoping



Patent: US20130101261, WO2012004547A1, EP2591387 A1

LP (< 1W) / Er-doped

HACC structure allows to overcome the limitation of standard H_2 or D_2 loading (out-diffusing)



- **Hole-Assisted Carbon Coated Erbium-doped optical fibers**

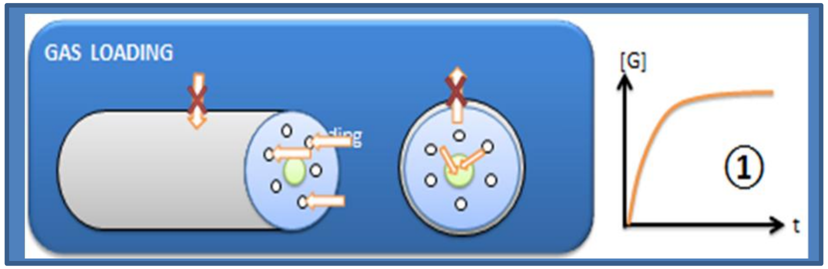
1. The core and cladding **composition is optimized** to reduce radiation sensitivity.

2. **Holes are created at the preform manufacturing stage**.

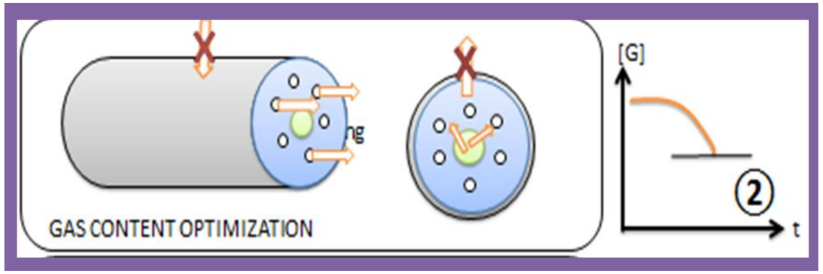
3. A hermetic **carbon coating** is then deposited.

LP (< 1W) / Er-doped

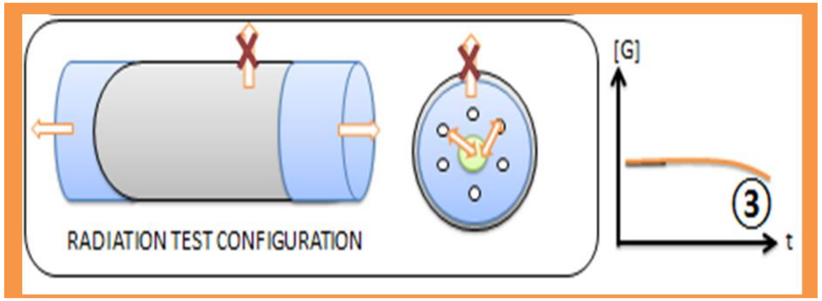
The H_2 or D_2 gas loading can be adjusted to obtain the best compromise between radiation hardness and optical performances



① **Loading of the HACC fiber** with H_2 or D_2 through the holes



② **Optimisation of the treatment -** control the gas level to attain the best compromise rad hardness/ optical performances, can be adapted to the mission profile



③ **Splicing** of the HACC loaded fiber to other parts of the EDFA

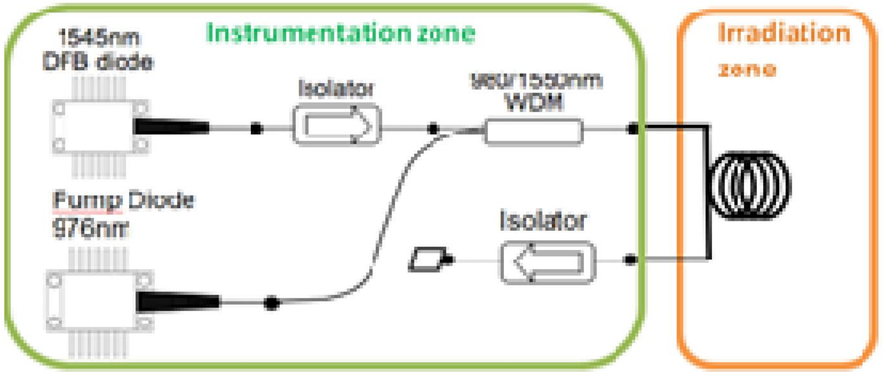
➤ **The kinetics of gas out-diffusion is decreased by ×100 compared to standard fibers**

LP (< 1W) / Er-doped

Radiation tests: radiation responses of the HACC fibers and amplifiers have been tested under X-ray, γ-ray and **proton** irradiations

❑ We compared the radiation responses of **3 fibers and 3 related EDFAs** made with
- ✓ **Radiation tolerant** optical fiber (RTAC)
- ✓ **HACC** fiber **without D2** loading (HACCwoD2)
- ✓ **HACC** fiber **with D2** loading (HACCwD2)

❑ **All EDFAs present comparable performances before irradiation** (but different RE fiber lengths)



Used HACC fiber was kept for 440h @ 80°C + 5 months at RT before the tests

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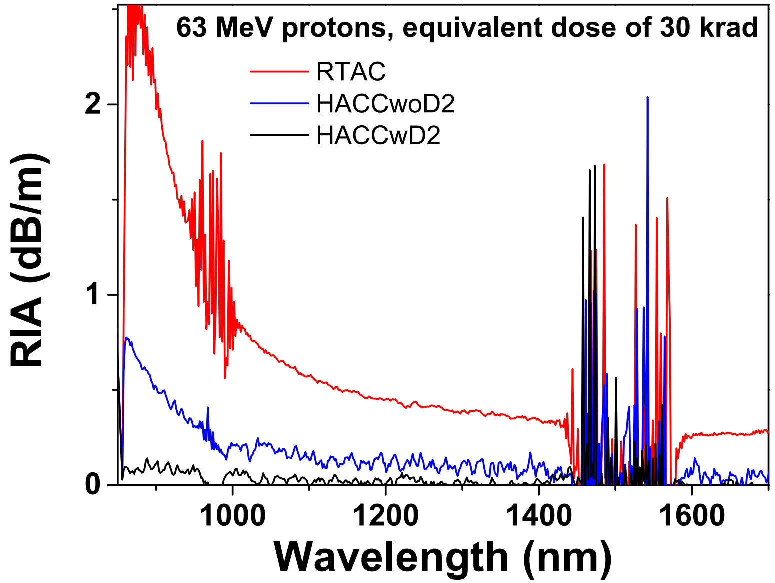
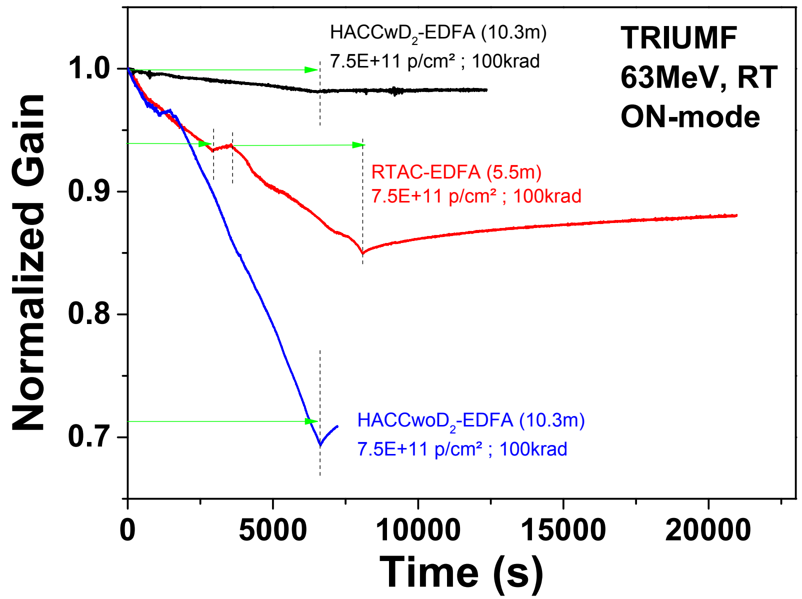
LP (< 1W) / Er-doped

Radiation tests: new composition improves the fiber RIA and new HACC structure improves even more the amplifier proton response





- ❑ The **new composition** is efficient to reduce Al-related background RIA
- ❑ **HACC with D2** suppresses background RIA
- ❑ **EDFA-HACC without gas** is not rad hard ➔ due to larger RE-fiber length.
- ❑ **EDFA-HACC with D2** strongly reduces the gain degradation **(less than 2% after 100 krad as equivalent dose)**

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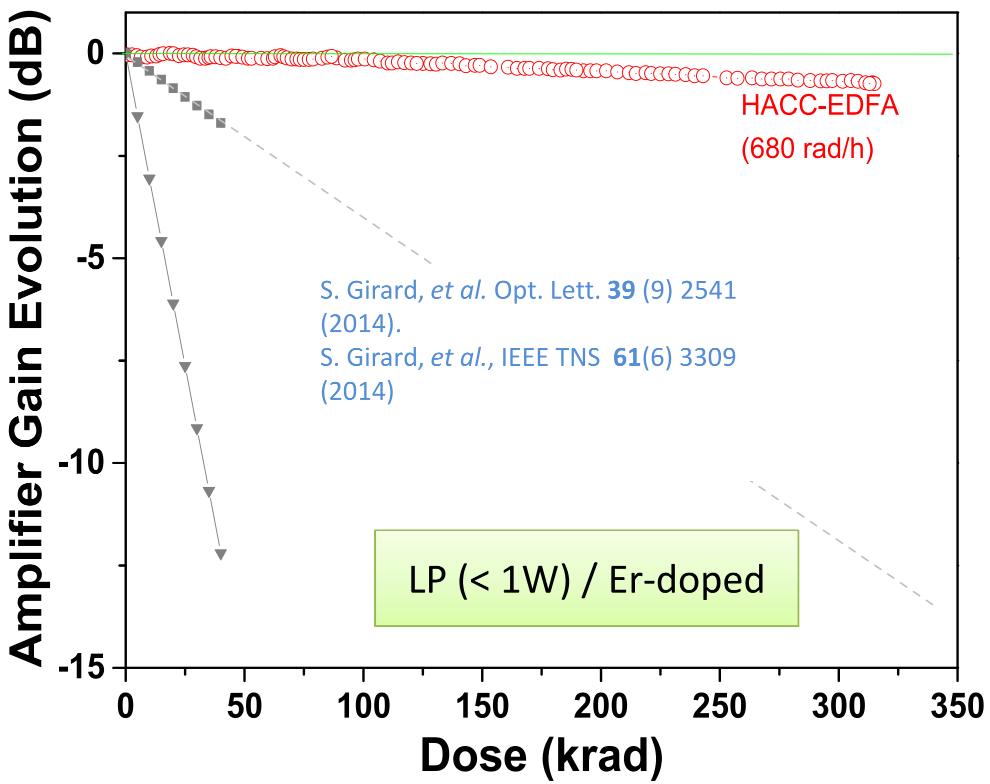
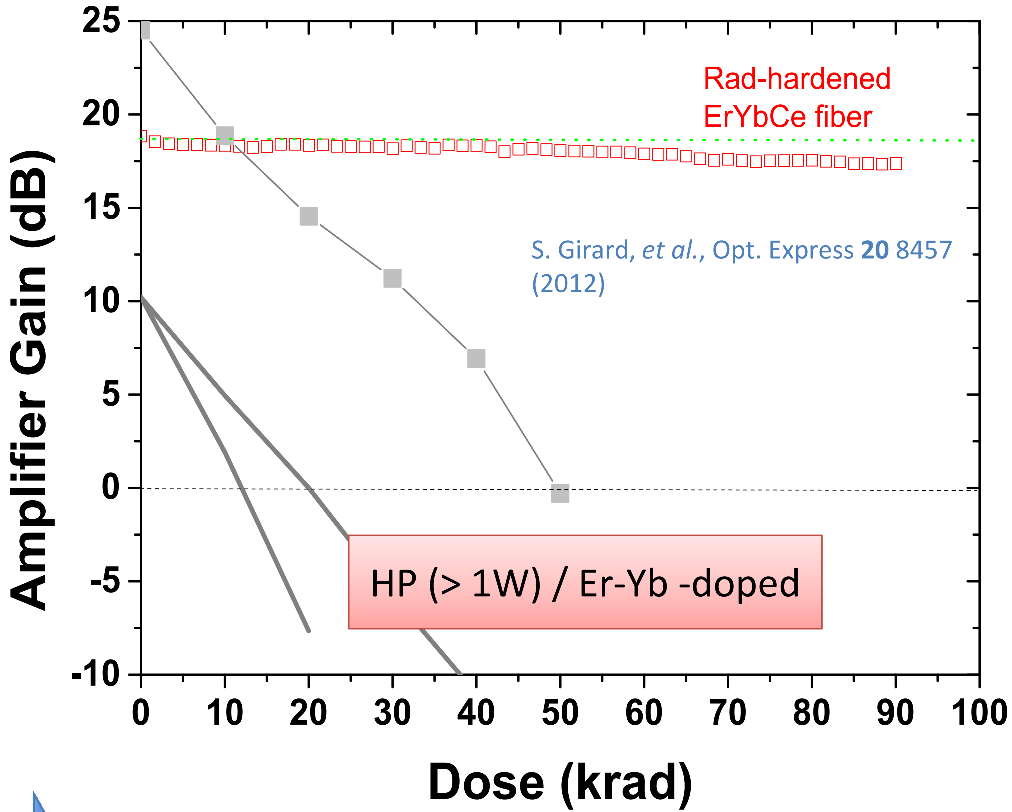
State-of-the-art in 2016

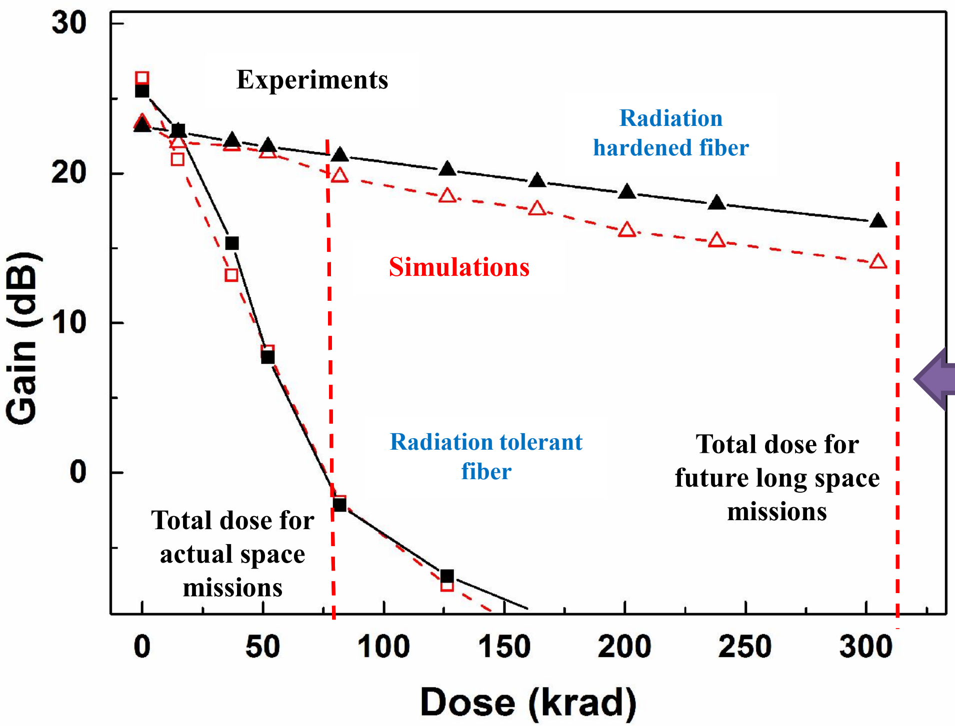
Radiation-hardened Er and Er/Yb-doped fibers exist today even for the most challenging missions



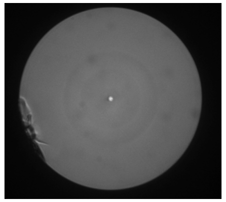


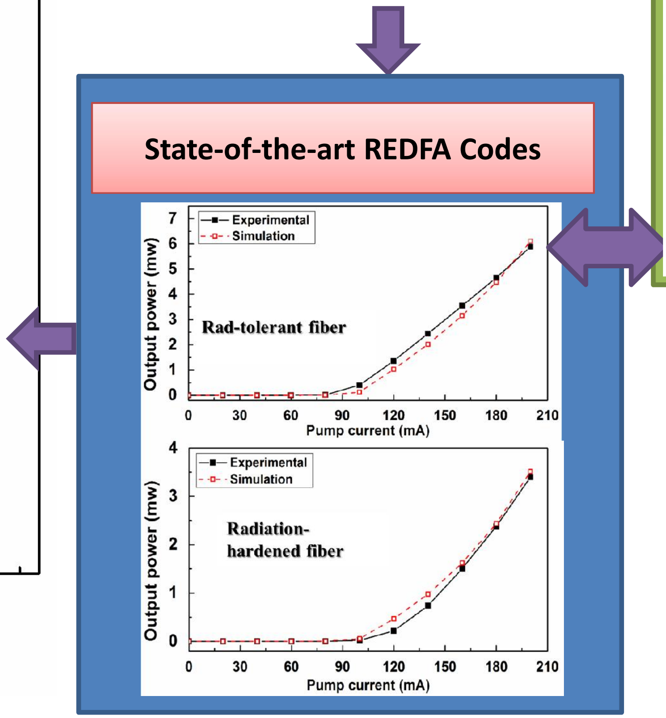
- Space qualification of HACC fibers in progress (CNES)
- Er-Yb rad hard fibers commercially available

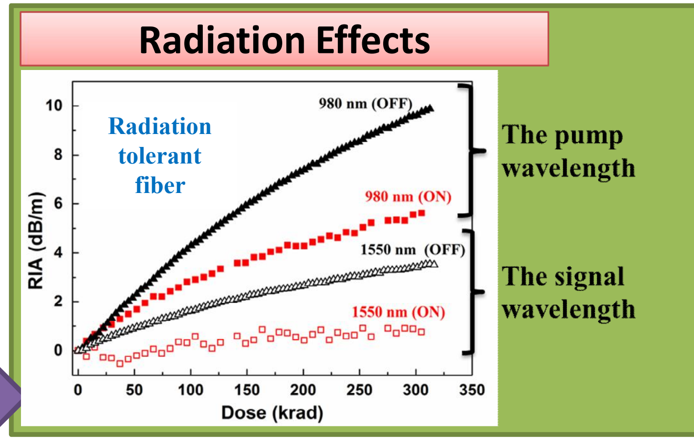
Current research (PhD A. Ladaci) focuses on building simulation tools for prediction of radiation and temperature effects on EDFA and EYDFA



Fiber properties (geometry, spectroscopic properties,…)







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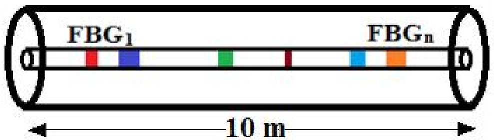
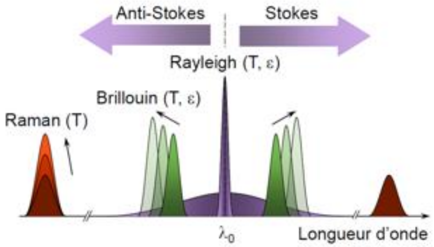
Part 3: Recent Advances on Optical Fiber Sensing in Harsh Environments

Various OFS technologies exist, exploiting the *a*-SiO_2 structural and optical properties



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

DISCRETE SENSING
(temperature, strain)



- 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*)

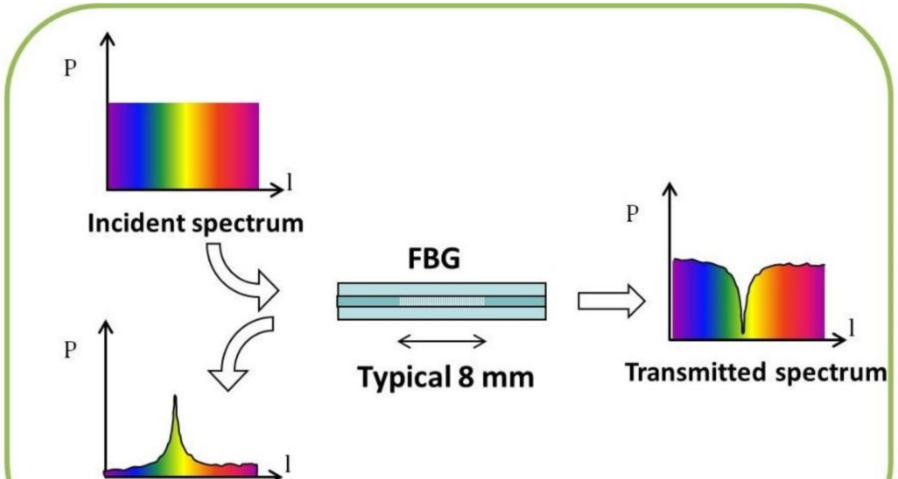
PUNCTUAL, ONLINE, OFFLINE SENSING

Since Fukushima event, OFS vulnerability studies are fueled by the nuclear industry
➔ almost all techniques can be used in harsh environments

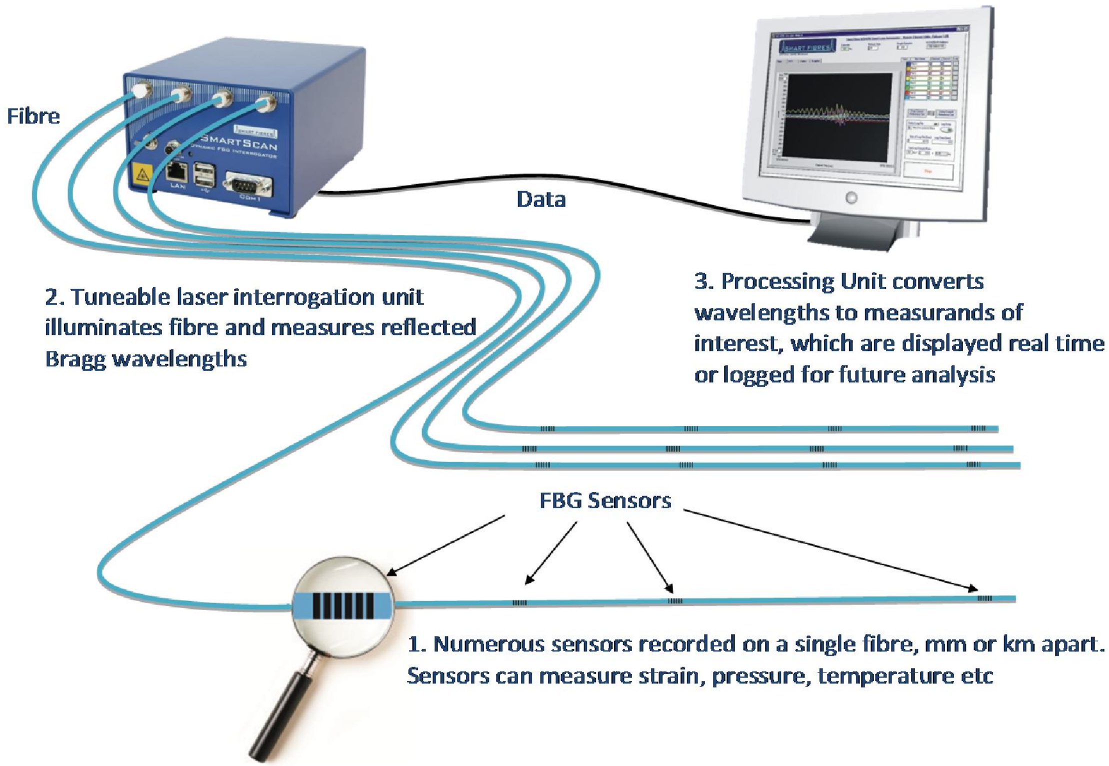
FBG Temperature & Strain Sensing in Nuclear Industry

❑ 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

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

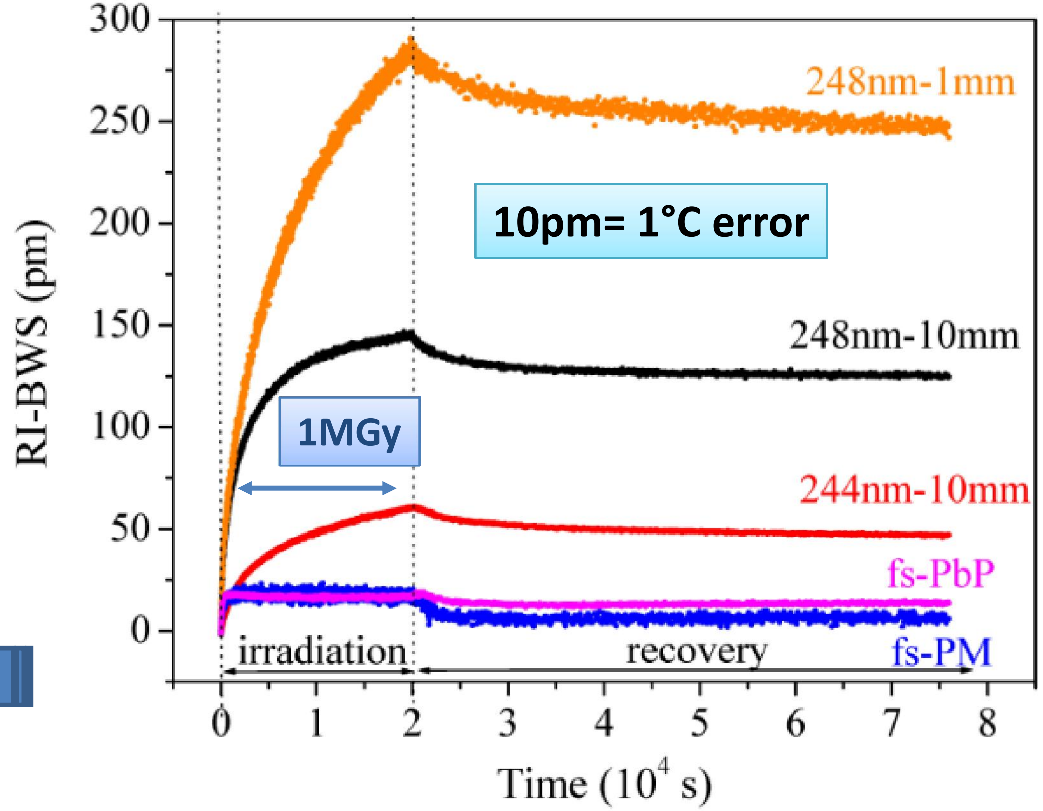
- ➢Degradation of OF ➔ RIA
- ➢Influence on the FBG properties:

Amplitude: possible FBG erasing under irradiation ➔ loss of OFSfunctionality

Bragg Wavelength Shift: error on T measurements

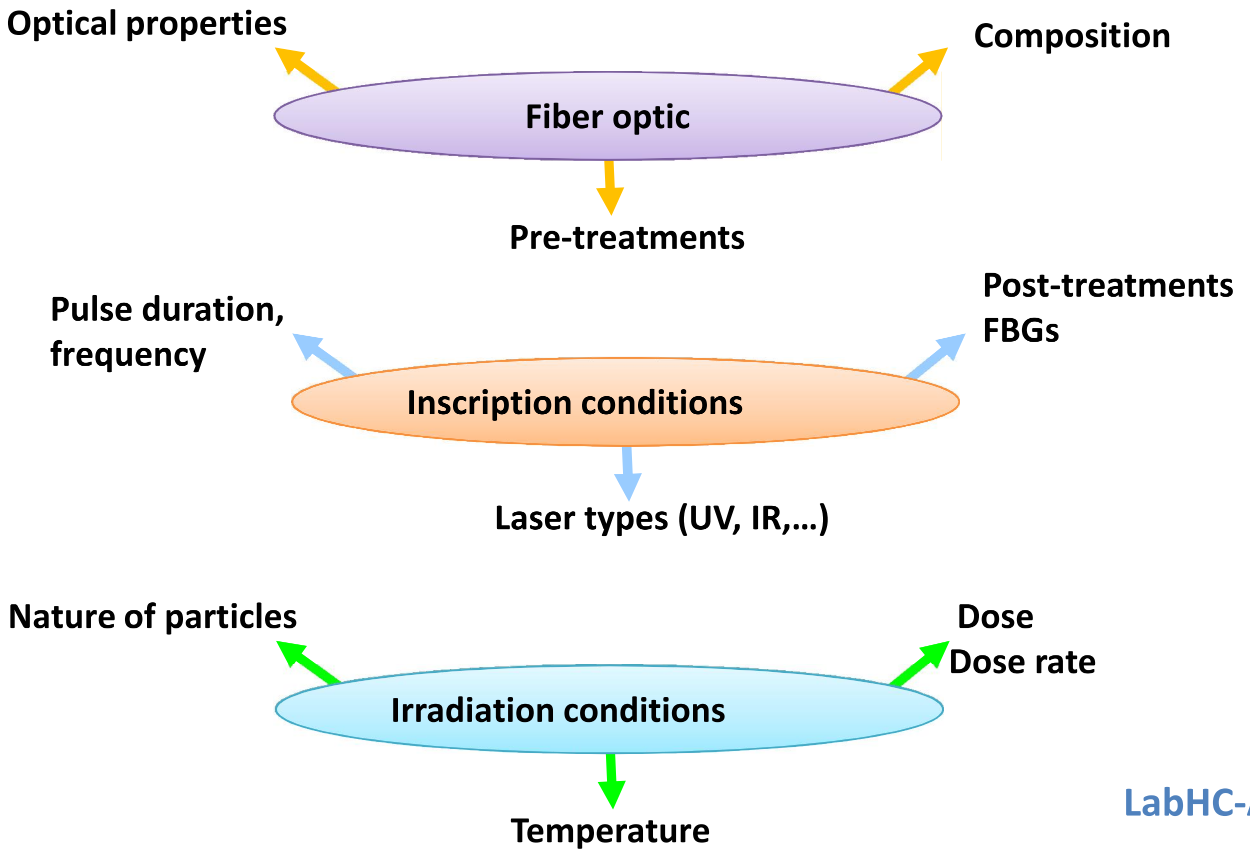
➔ OFS performance degradation

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



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

Parameters impacting the FBG response

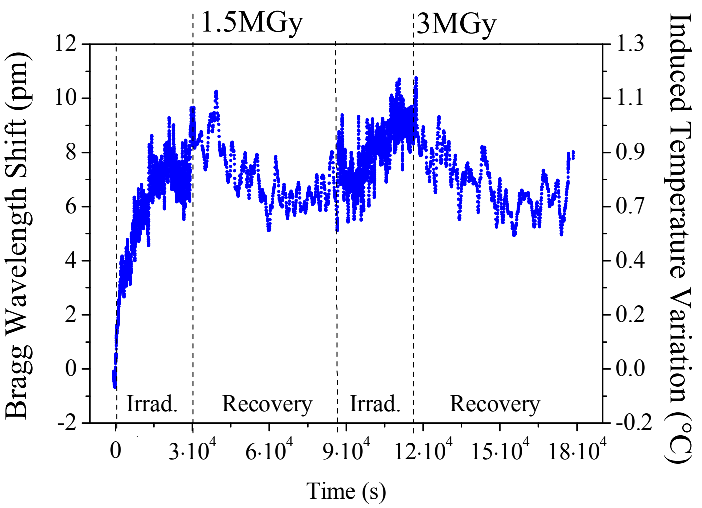


LabHC-AREVA patent (Dec. 2013)

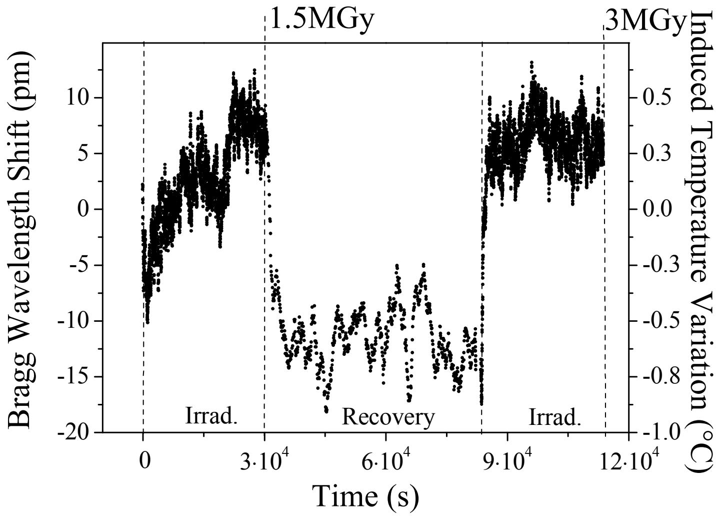
➡ **We identified a procedure to develop RH FBGs for high T operation (up to 350°C)**

RH-FBGs are made with *fs* lasers following the patented procedure into RH-OF

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



ROOM TEMPERATURE (~25°C)



HIGH-T (~230°C)

➡ These RH FBGs also present the best response to high-T (300°C) and high fast neutron fluence up to 3×10^{19}n/cm² (collaboration with CEA DEN/DRT)

eit Knowledge & Innovation Community
KIC InnoEnergy

HOBAN

LabHC - *AREVA – FINT– iXBlue – SmartFibres*

Development of hard optical fiber Bragg grating sensors (2015 -2017)

The vulnerability and hardening studies of OFS technologies is under progress

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

DISCRETE SENSING
(temperature, strain)

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

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

- Dosimetry
  - RIA (*active, distributed*)
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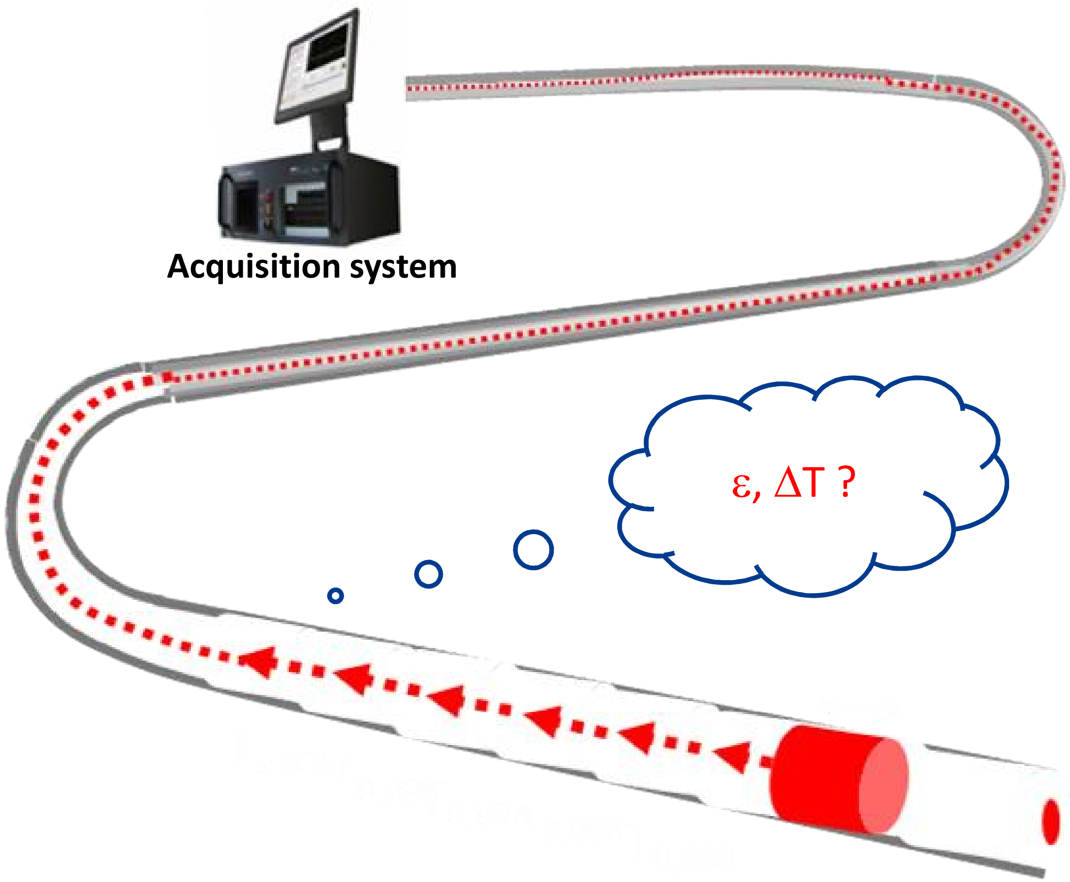
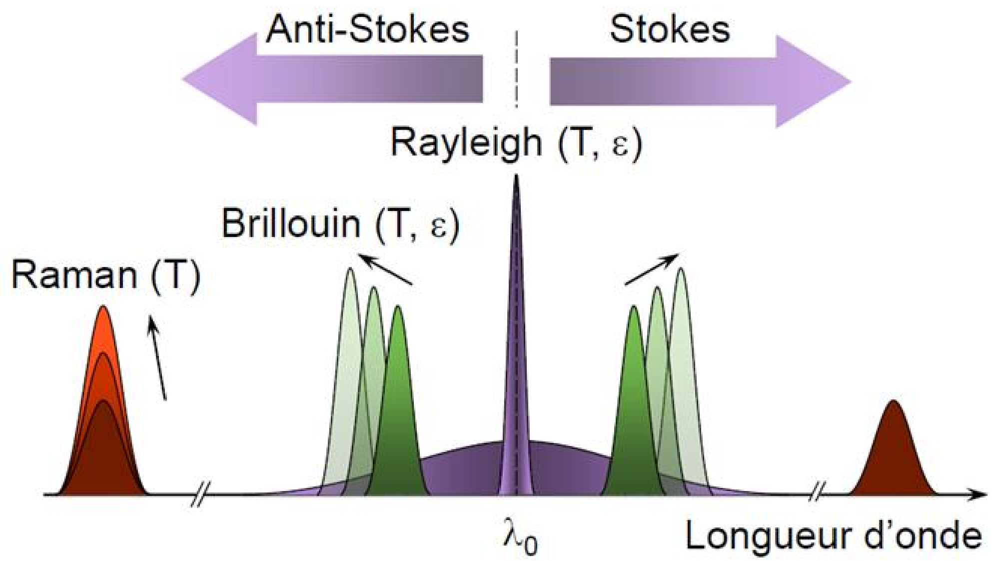
PUNCTUAL, ONLINE, OFFLINE SENSING

Distributed sensing based on backscattered light into OFs





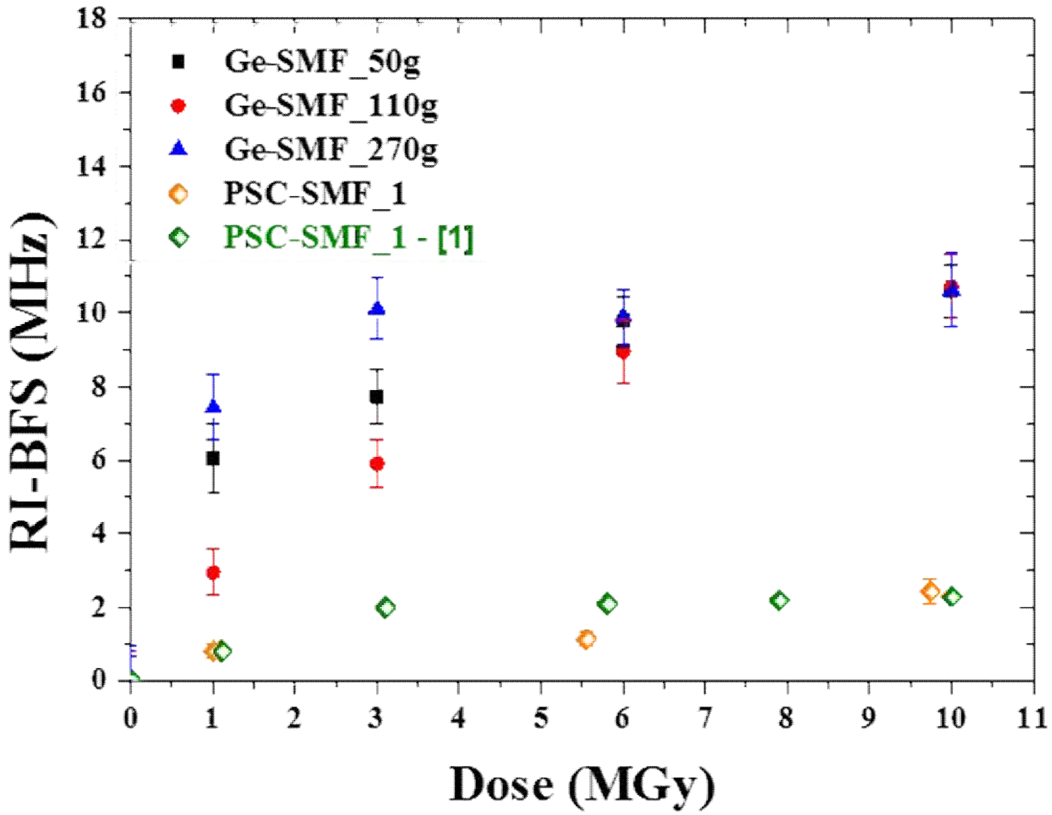
PhD thesis Xavier Phéron
PhD thesis Serena Rizzolo
PhD thesis Chiara Cangialosi
PhD thesis Isabelle Planes

Brillouin-based distributed temperature measurements is possible at MGy dose levels

- Radiations affect Brillouin sensors by different ways:
  - **RIA** limits the possible distance range
  - **Radiation shifts the BFS ➔** direct error on the T or strain measurement

By using best optical fibers, it is possible to limit the error below 1-2°C at MGy dose over hundredths of meters

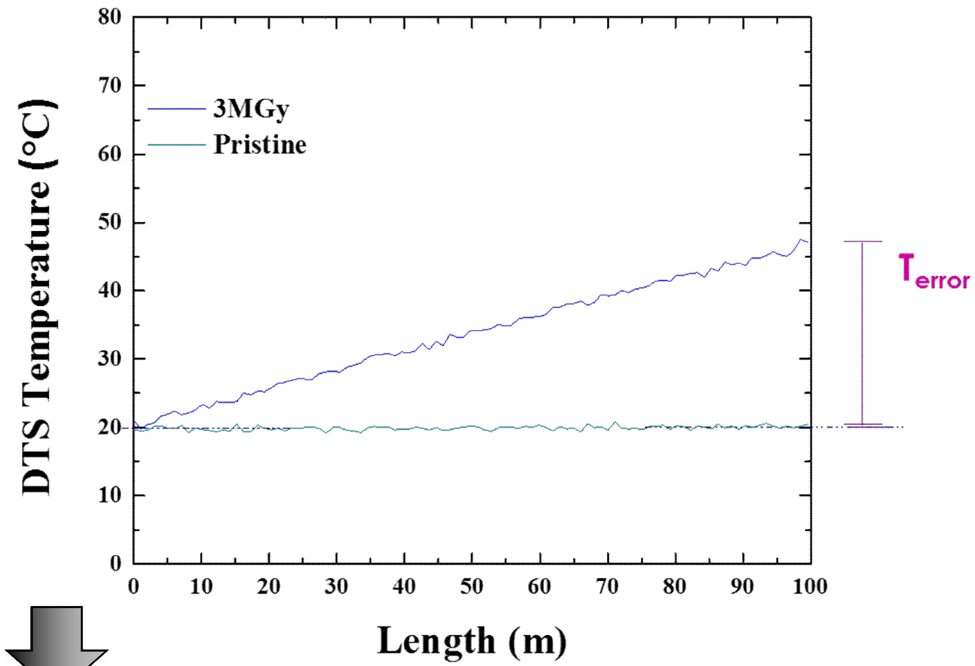
C. Cangialosi, PhD Thesis, 2016



Raman-based distributed temperature (RDTS) measurements are not possible with standard single-ended (SE) commercial sensors

- Radiations affect Raman sensors by different ways:
  - **RIA limits the possible distance range** (x2 in the case of double-ended)
  - **Radiation can affect the S/AS ratio➔** direct error on the T measurement due to ΔRIA

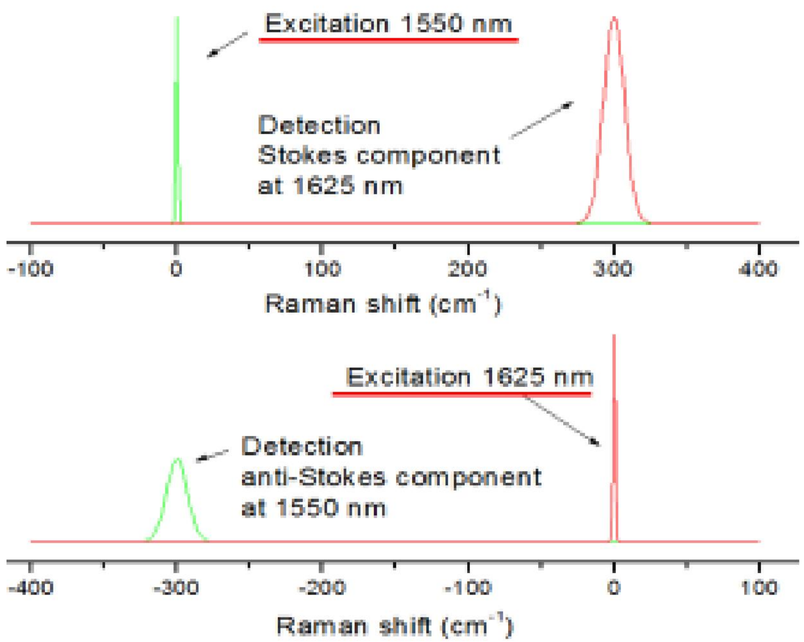
C. Cangialosi, PhD Thesis, 2016

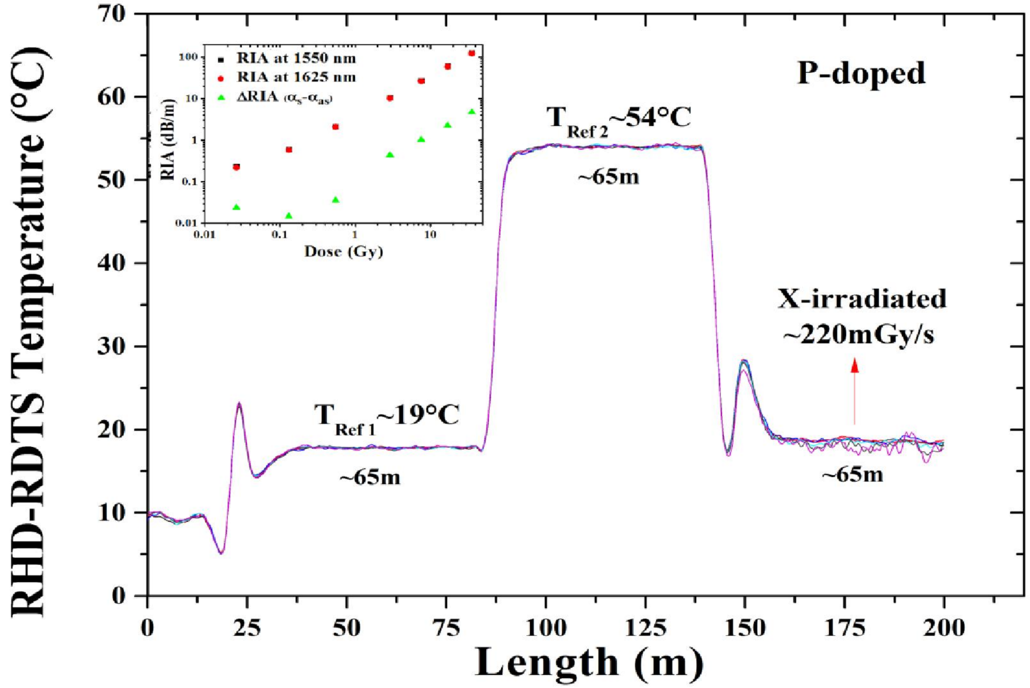


Hardening is not possible by components ➔ the architecture of the sensors must be adapted

A Hardening-by-System approach allows us to perform Raman measurements at high doses

Di Francesca et *al.*, *IEEE TNS, accepted, 2016.*



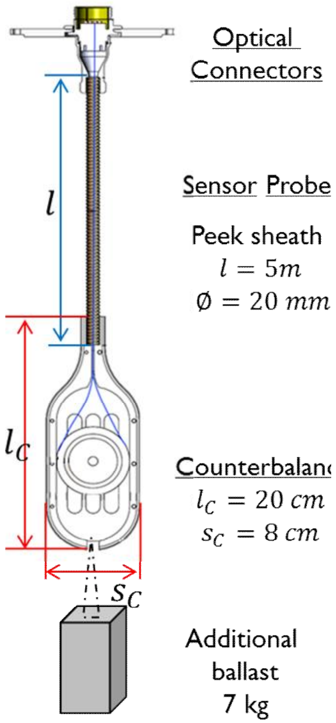


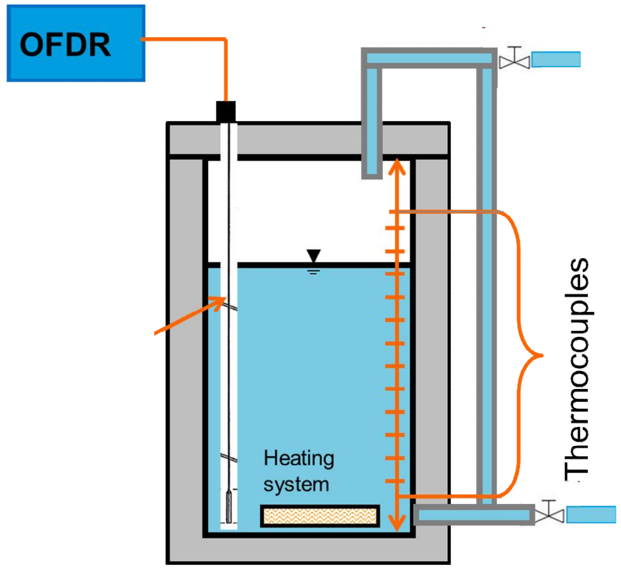
This new SE-RDTS architecture limits both RIA and ΔRIA issues

Rayleigh-based OFS: 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>**

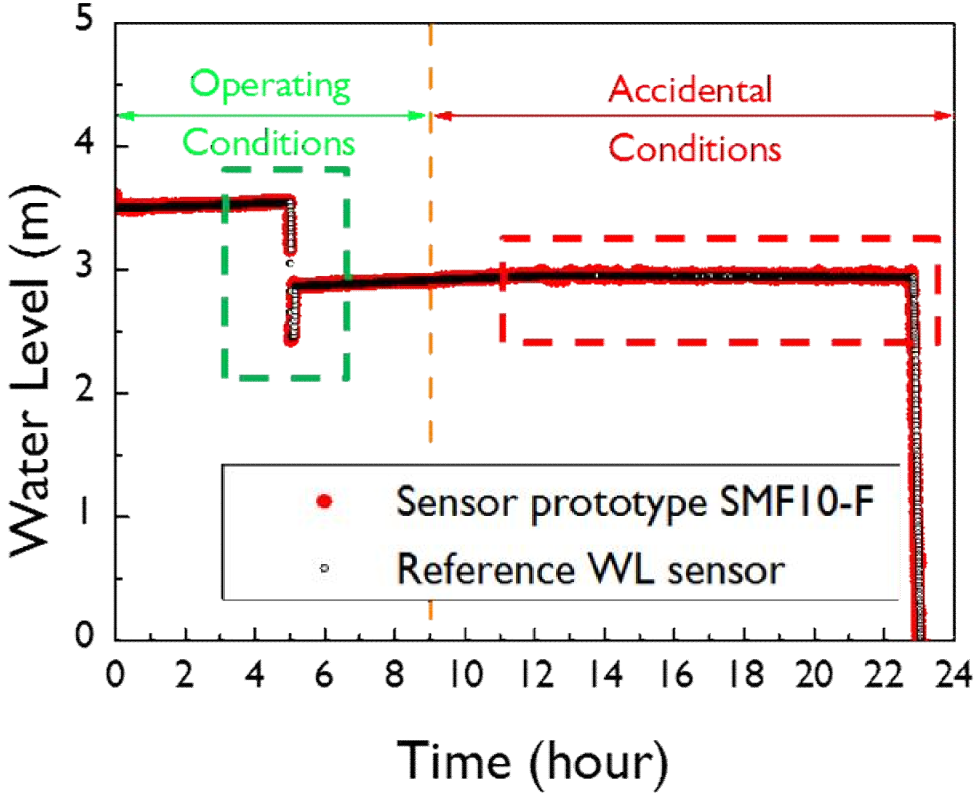
➡ **Very recent results demonstrated the potential of this technique for monitoring T, strain in nuclear facilities**

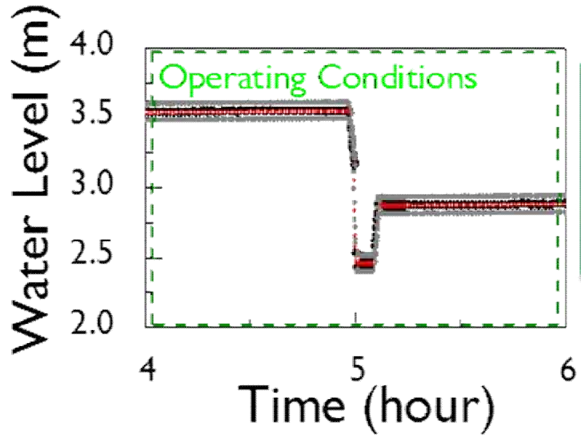




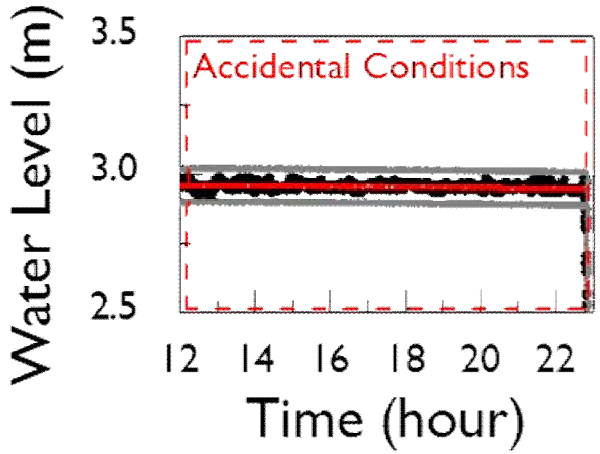
S. Rizzolo, et al., Optics Express, vol.23 (15), 18998 , 2015.
S. Rizzolo, et al., Optics Letters, 2015 ; S. Rizzolo et al., IEEE TNS, 2015.
AREVA – LabHC, 2015 pending patents

Water level is well detected with a F-doped OF with polyimide coating





Incertitude on WL: 1 cm



Incertitude on WL: 3 cm

S. Rizzolo, PhD Thesis, 2016

The vulnerability and hardening studies of OFS technologies is under progress

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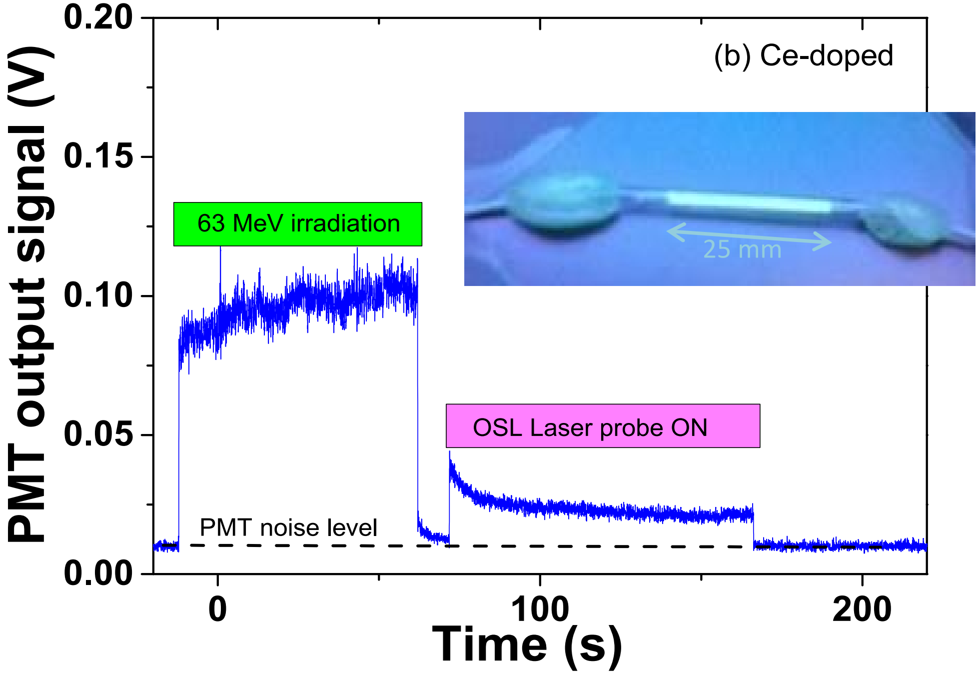
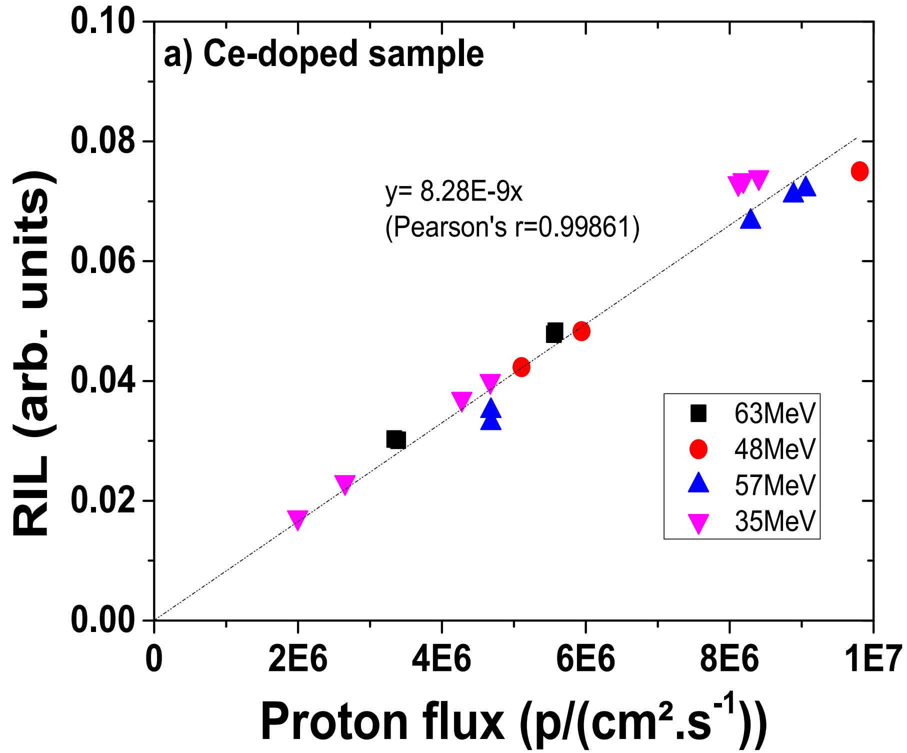
PUNCTUAL, ONLINE, OFFLINE SENSING

Proton flux monitoring : RIL + OSL with Ce-doped glasses

S. Girard et al., IEEE TNS, in press, 2016

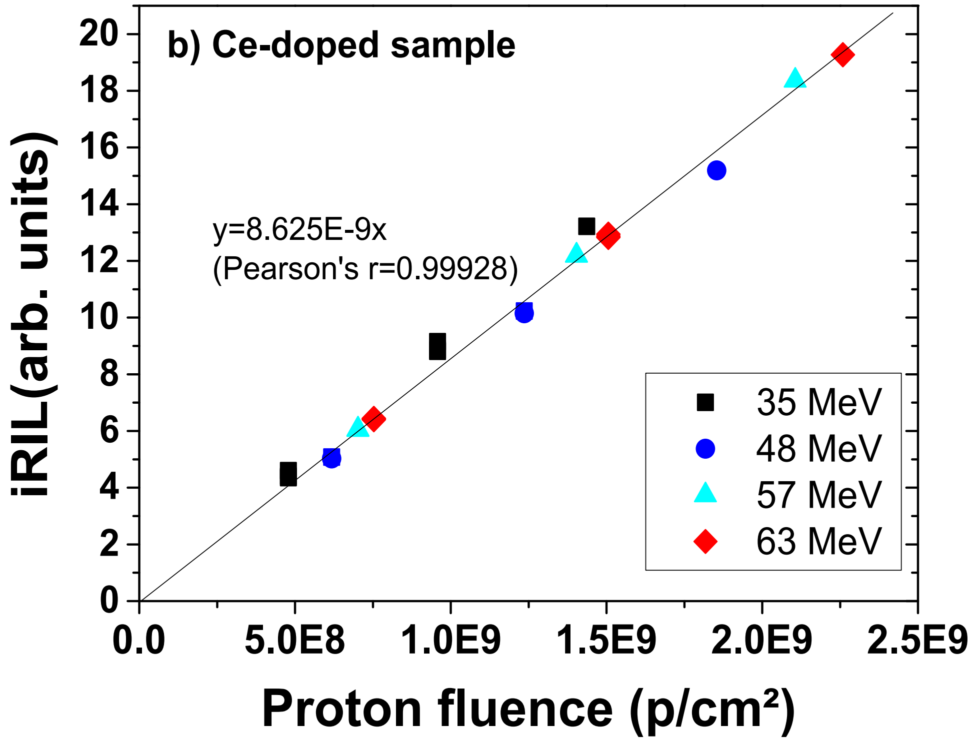




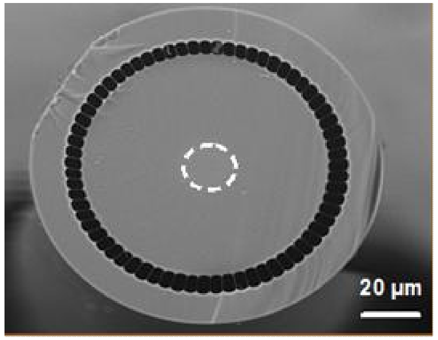
➡ **This technique permits to monitor the flux with ms resolution**

And the Proton fluence too…

S. Girard et al., IEEE TNS, in press, 2016



Perspectives



➡ **This technique allows monitoring the fluence too by integration of the proton flux**

Conclusions

- Optical fibers are quickly integrated in facilities encountering radiations

- Future challenges concern the **functionalization of these fibers** to monitor parameters such as T, strain, pressure, liquid level, vibrations,….
  - *FBGs, Brillouin, Raman, Rayleigh-based sensors….*

- Overcoming these future challenges will be possible through a **coupled simulation/experiments approach** to identify/predict the basic mechanisms describing the radiation effects in dielectrics

- The fundamental knowledge, developed experimental or simulation tools of the radiation effects community can bring new insights about the nature of point defects present in optical fibers or allow to tune the optical properties of silica glasses