HOBAN project –Development of radiation-tolerant fiber Bragg grating based temperature and strain monitoring sensors for nuclear industry

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Outline

I. Optical Fiber Sensors and Harsh Environments

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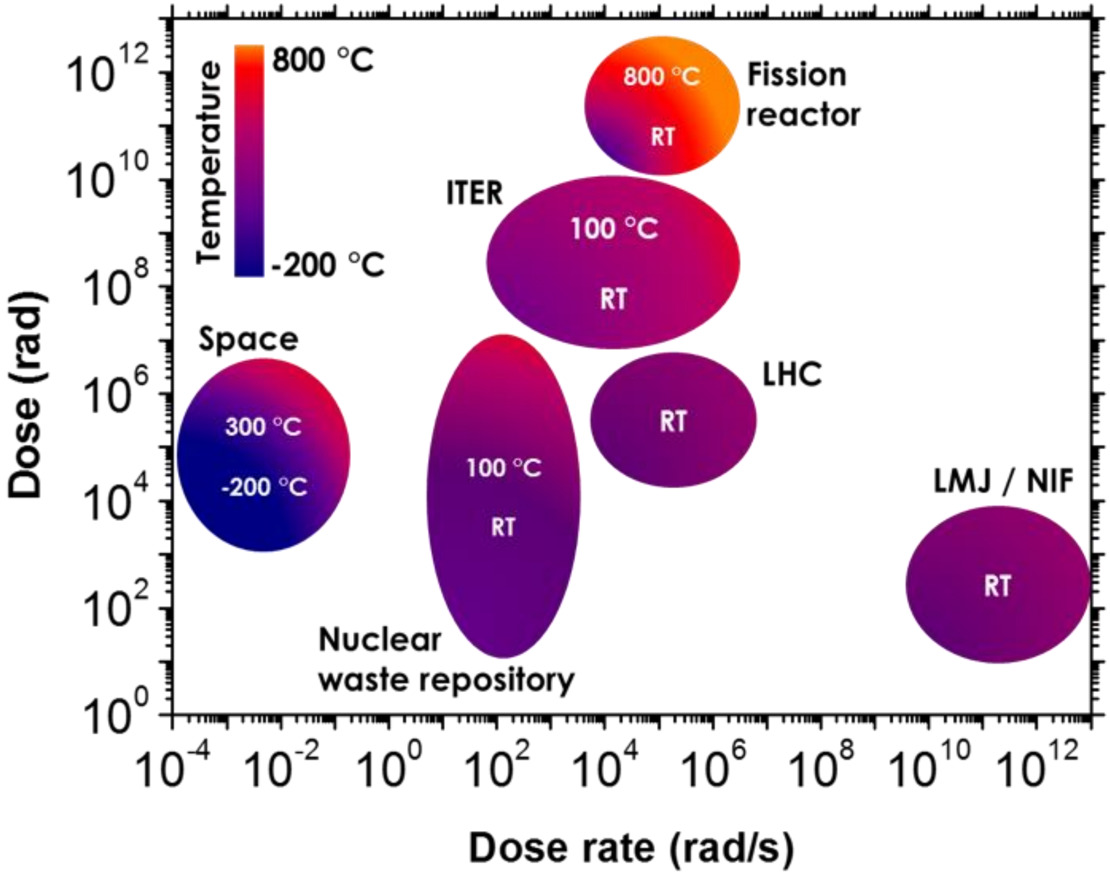
Applications for Optical Fiber Sensors: the harsh environments



The Optical Fiber Sensors present several advantages but their responses are influenced by radiation.

Advantages:

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

Limitations in HARSH ENVIRONMENTS:

The radiation :

- Degrades the optical fiber transmission properties
- Influences the OFS response

II. Fiber Bragg Grating based Sensors

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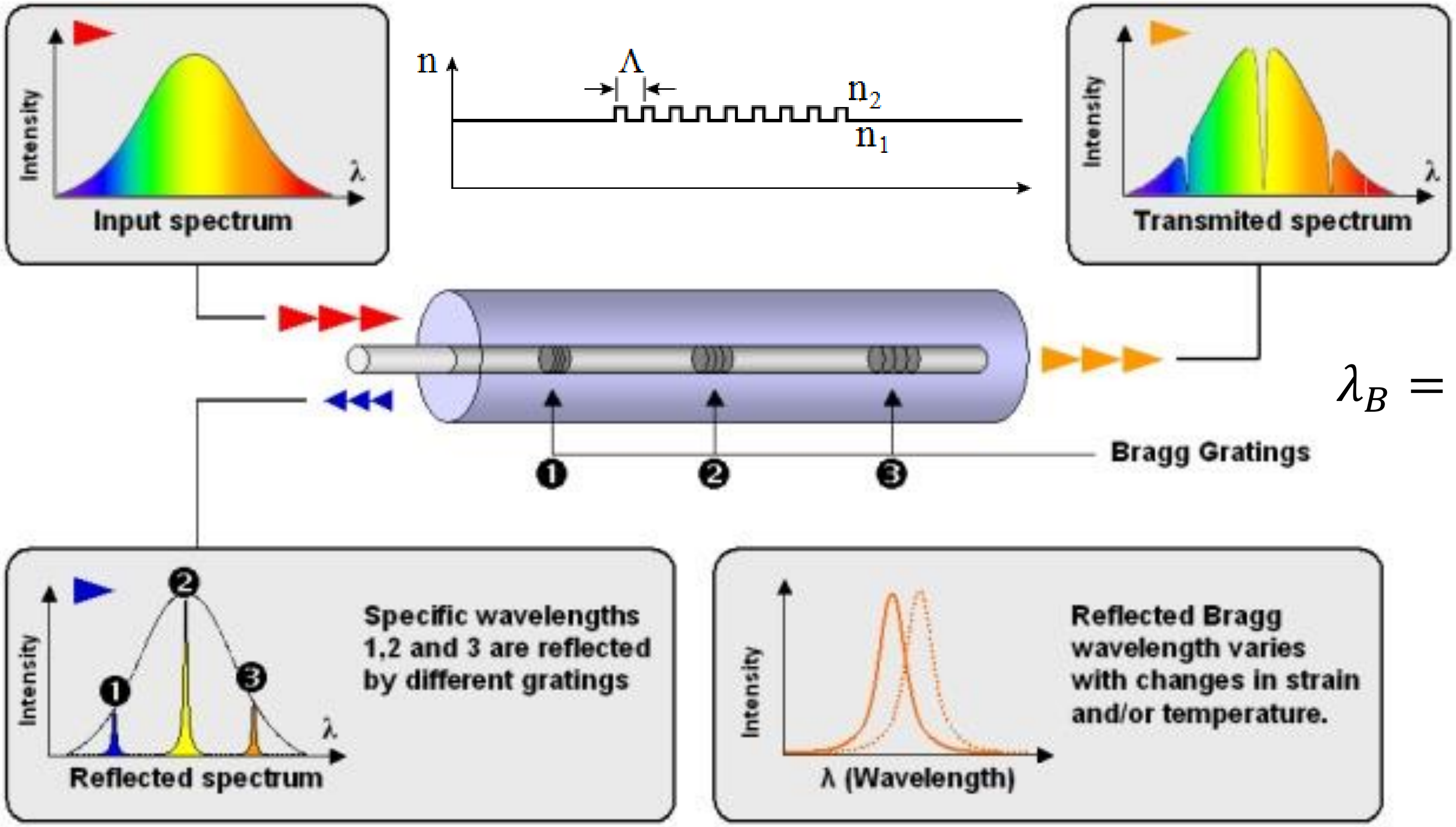
Fiber Bragg Gratings can be used as temperature and/or strain sensors.



$$\lambda_B = 2\, n_{eff}\, \Lambda$$

http://www.scaime.com/

Radiation influences the FBG response.

Radiation (X- or γ-rays) and/or Particles (neutrons, protons…)

⇩

Defects (**RIA**) and density change

⇩

Refractive index change and Grating pitch variation

Radiation-induced Bragg wavelength shift (RI-BWS)

⇩

$$\lambda_B = 2\, n_{eff}\, \Lambda$$

⇩

$$\frac{\Delta\lambda_B}{\lambda_B} = \frac{\Delta n_{eff}}{n_{eff}} + \frac{\Delta\Lambda}{\Lambda}$$

Peak amplitude reduction

⇩

Signal-to-noise ratio reduction

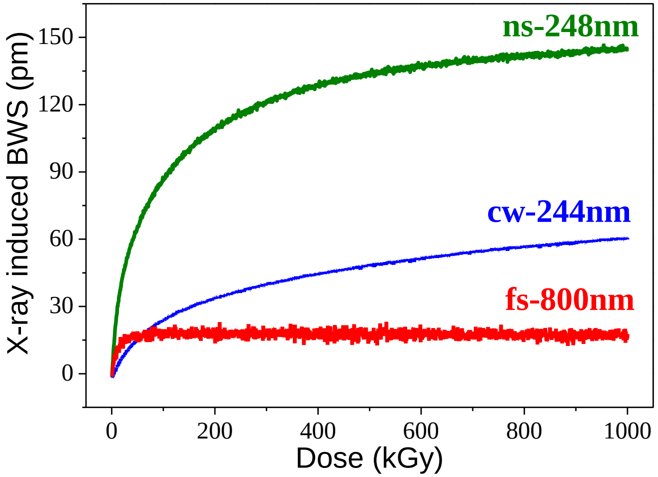
Gusarov et al., Transactions on Nuclear Science, 60, pp. 2037-2053 (2013).

The radiation response depends on several parameters.

- **Irradiation conditions:**
  - Dose and dose-rate
  - Irradiation temperature
  - Nature of irradiations
- **Optical fibers:**
  - Fiber composition
  - Optical properties
  - Pre-treatments
- **FBG inscription:**
  - Writing laser
  - Inscription conditions
  - Post-treatments

The higher the dose-rate the larger the RI-BWS.
Fernandez et al., IEEE Tran. Nucl. Sci. 49(6), 2002.

The choice of radiation-resistant fibers does not ensure resistant FBGs.
Henschel et al., IEEE Trans. Nucl. Sci., 55 (4), 2008.



III. Rad-Hard FBG based sensors

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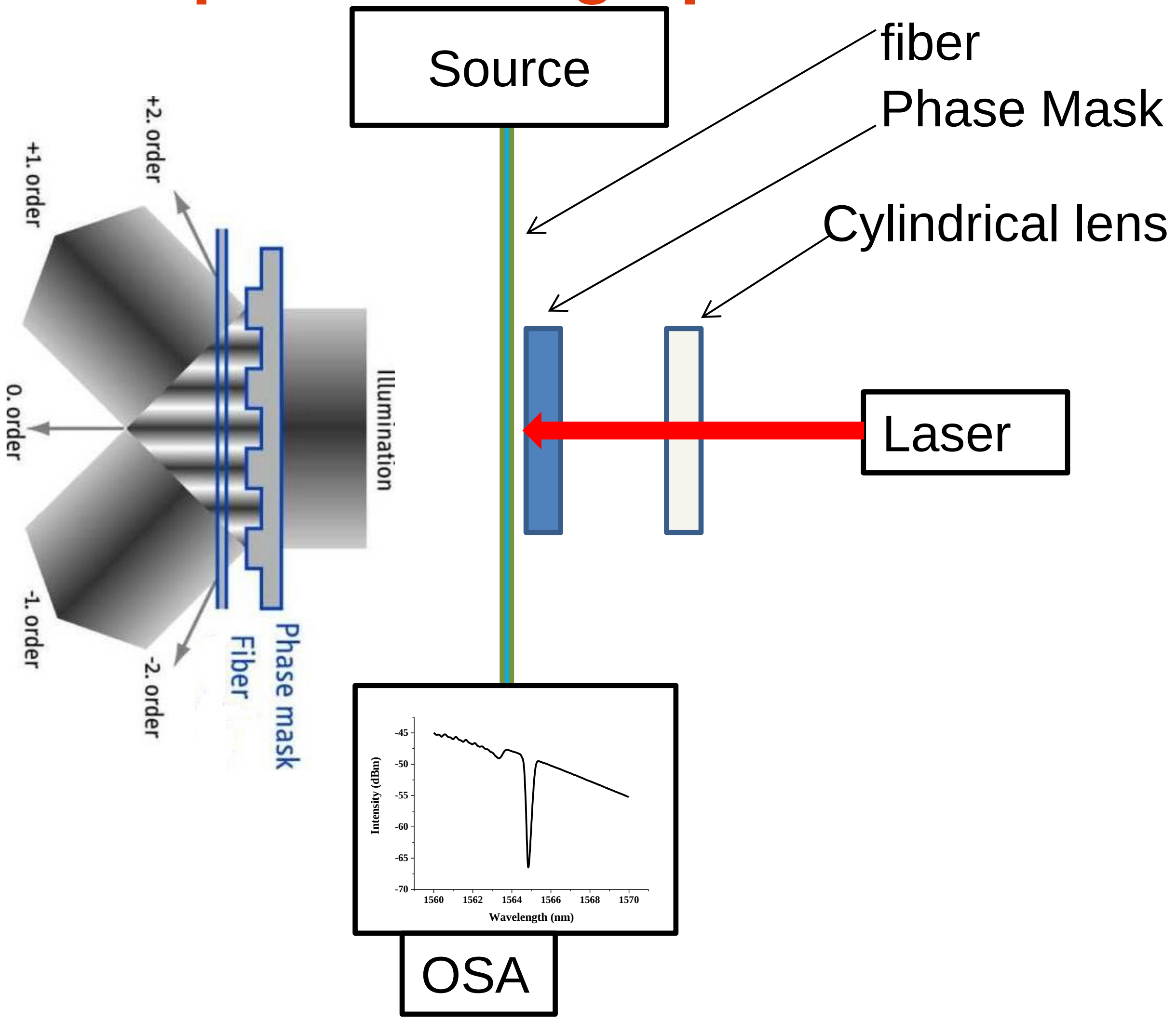
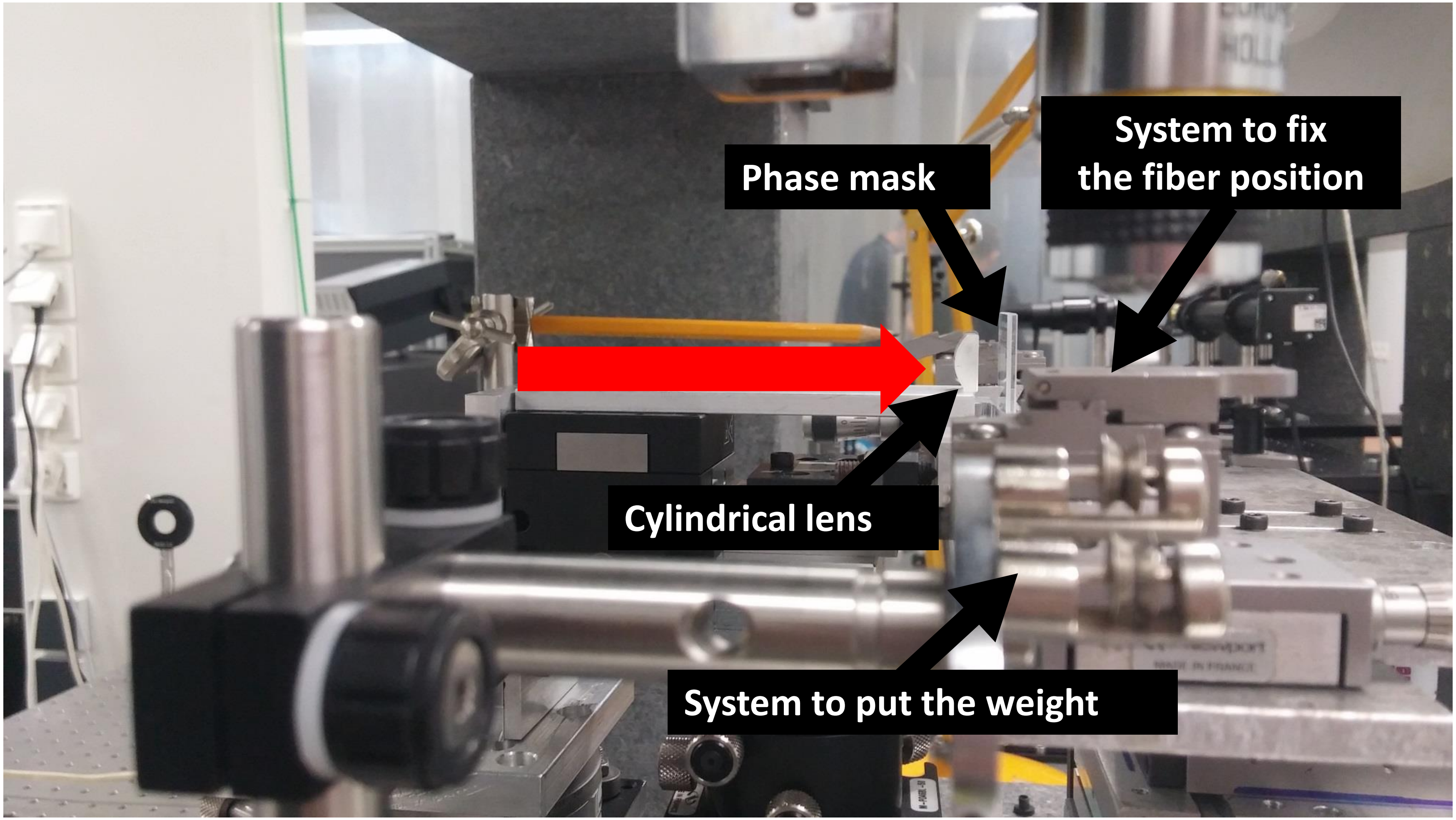
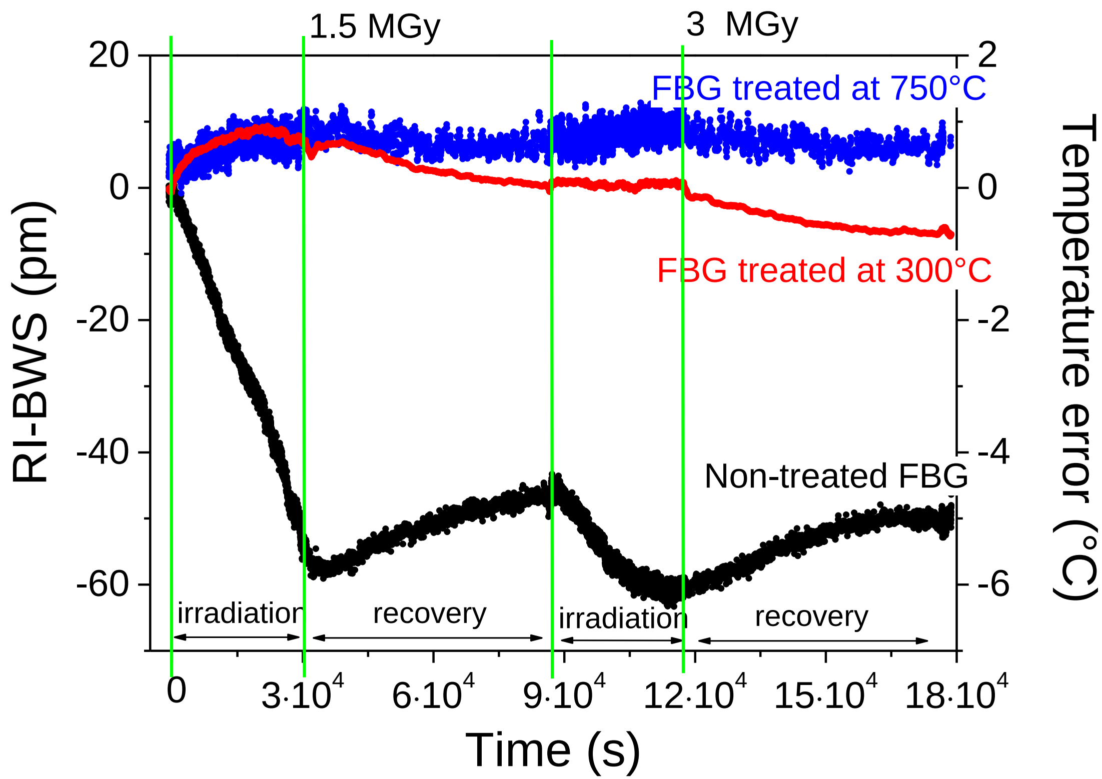
fs-FBG inscription through phase-mask



fs-FBG inscription through phase-mask



A thermal treatment at 750°C increase the radiation resistance of fs-FBGs.

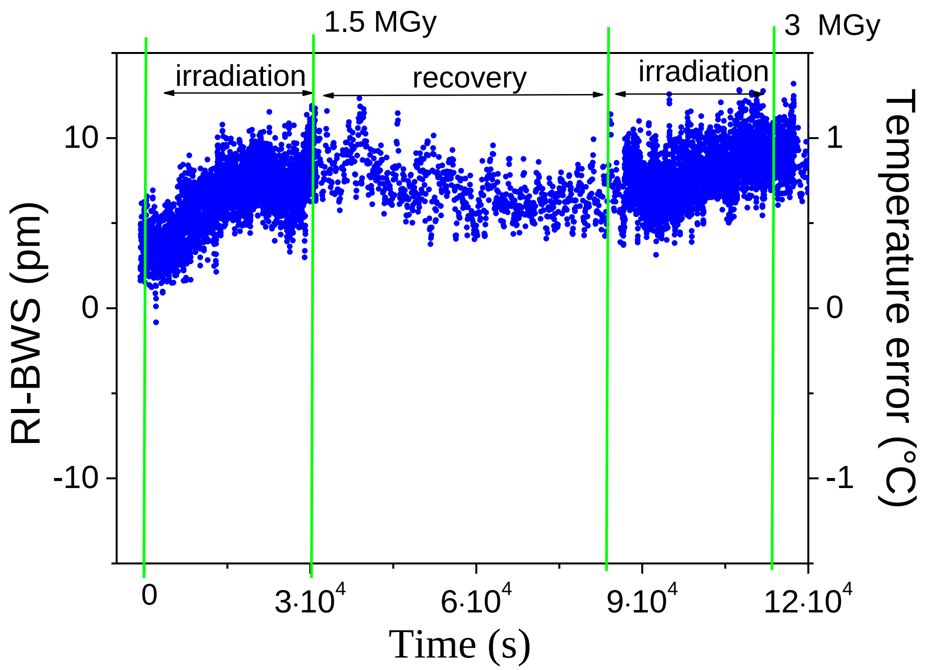


at ROOM TEMPERATURE

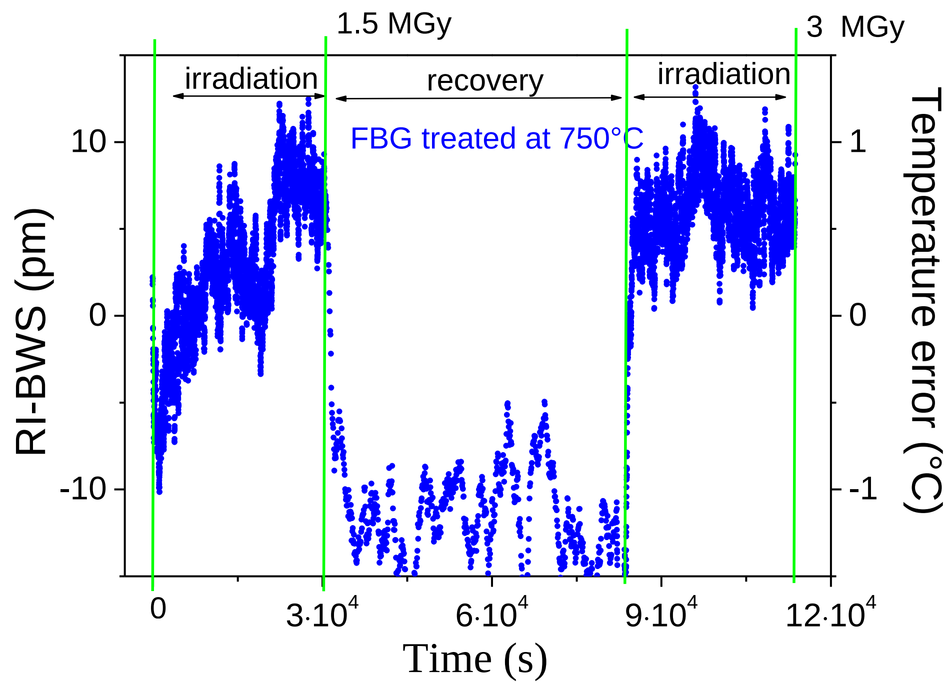
Morana, et al. Optics Letters 39 (18), pp. 5313 (2014).

The temperature error induced by X-rays up to 3 MGy dose is lower than ±1°C for irradiation temperatures between 25 and 230°C.

at 25°C

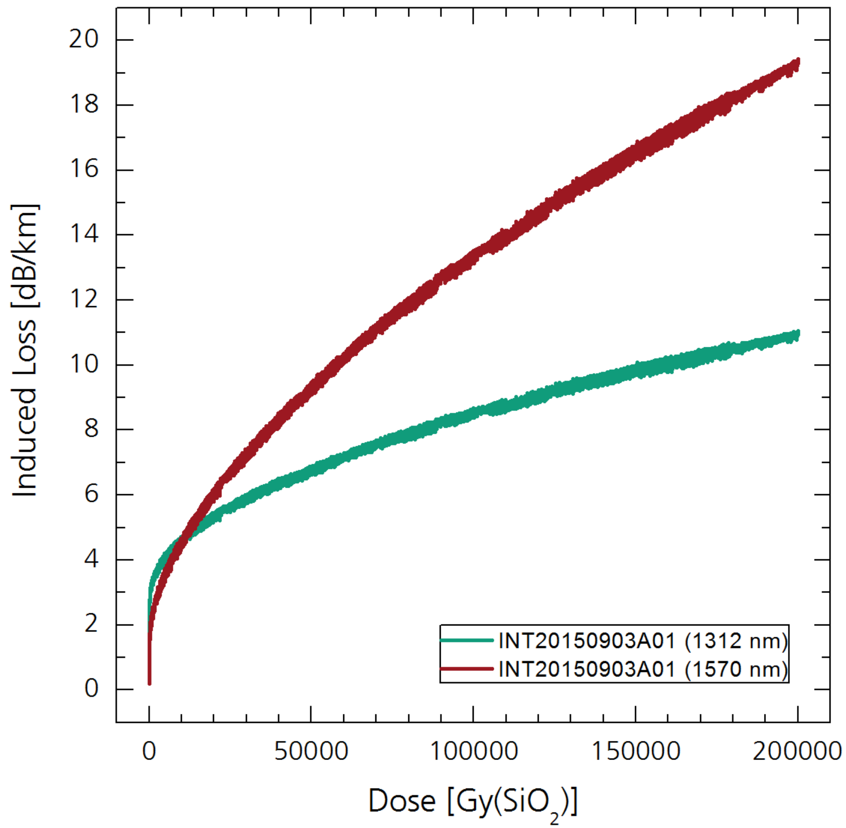


at 230°C



Morana, et al. Optics Letters 39 (18), pp. 5313 (2014).

The γ-rays induced losses at 1550 nm are only 20 dB/km at 200 kGy.



For 100 m long fiber, at 200 kGy the signal is only attenuated by 2 dB.

Kuhnhenn, et al. accepted to be published in Transaction on Nuclear Science (2017).

V. Hoban FBG response under **X-rays at room temperature**: a study on FBG inscription

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A study of the Hoban FBG response under X-rays on the grating inscription.

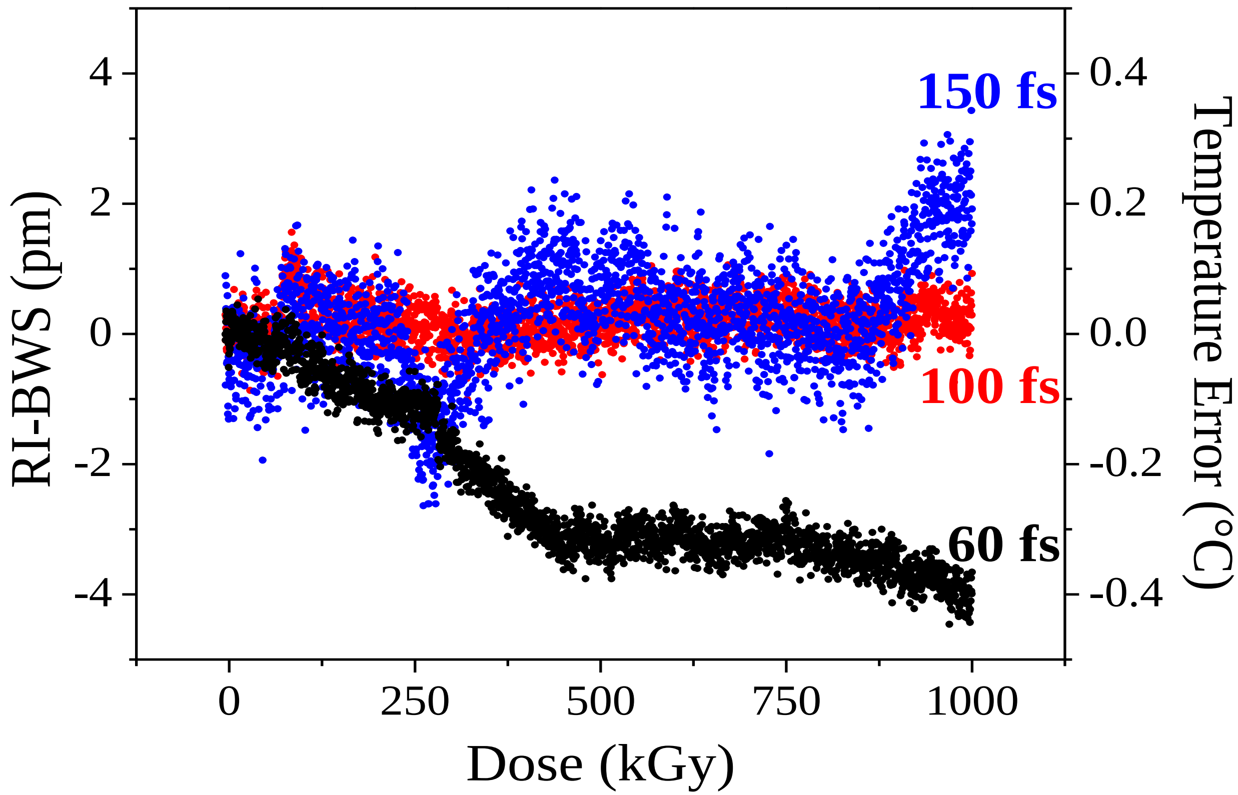
- **Irradiation conditions:**
  - **Dose and dose-rate** → Dose up to 1 MGy; Dose-rate: 1 to 50 Gy/s
  - Irradiation temperature
  - Nature of irradiations

- **Optical fibers:**
  - Fiber composition: F-doped or pure silica core fibers
  - **Optical properties**
  - Pre-treatments

- **FBG inscription:**
  - Writing laser: fs-lasers at 800 nm
  - **Inscription conditions** → Laser pulse width : (60 – 150) fs; Laser power density
  - Post-treatments: annealing at 750°C

The radiation-resistance of Hoban FBG does not depend on the **laser pulse width**.

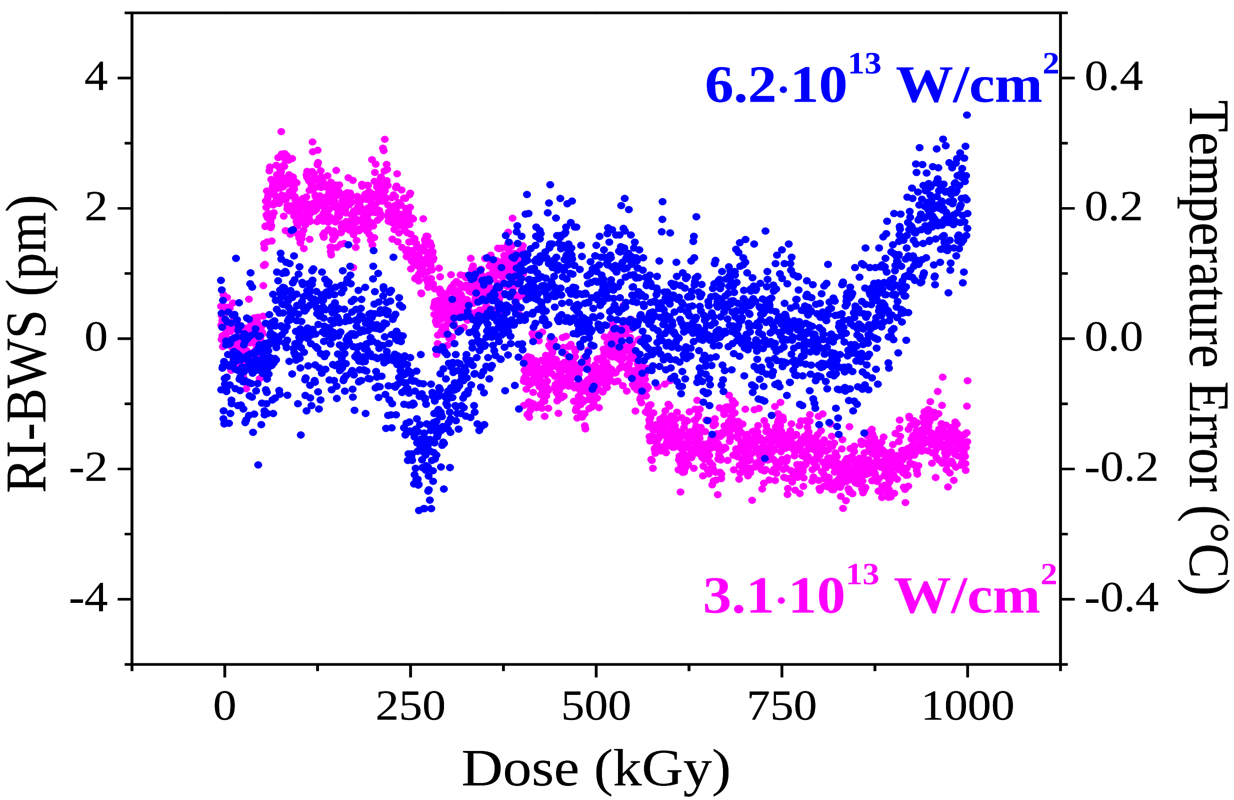
Power density ≈ $6 \cdot 10^{13}$ W/cm²



Dose-rate=50 Gy/s
Room temperature

The radiation-resistance of Hoban FBG does not depend on the **laser power density**.

Laser pulse width = 150 fs



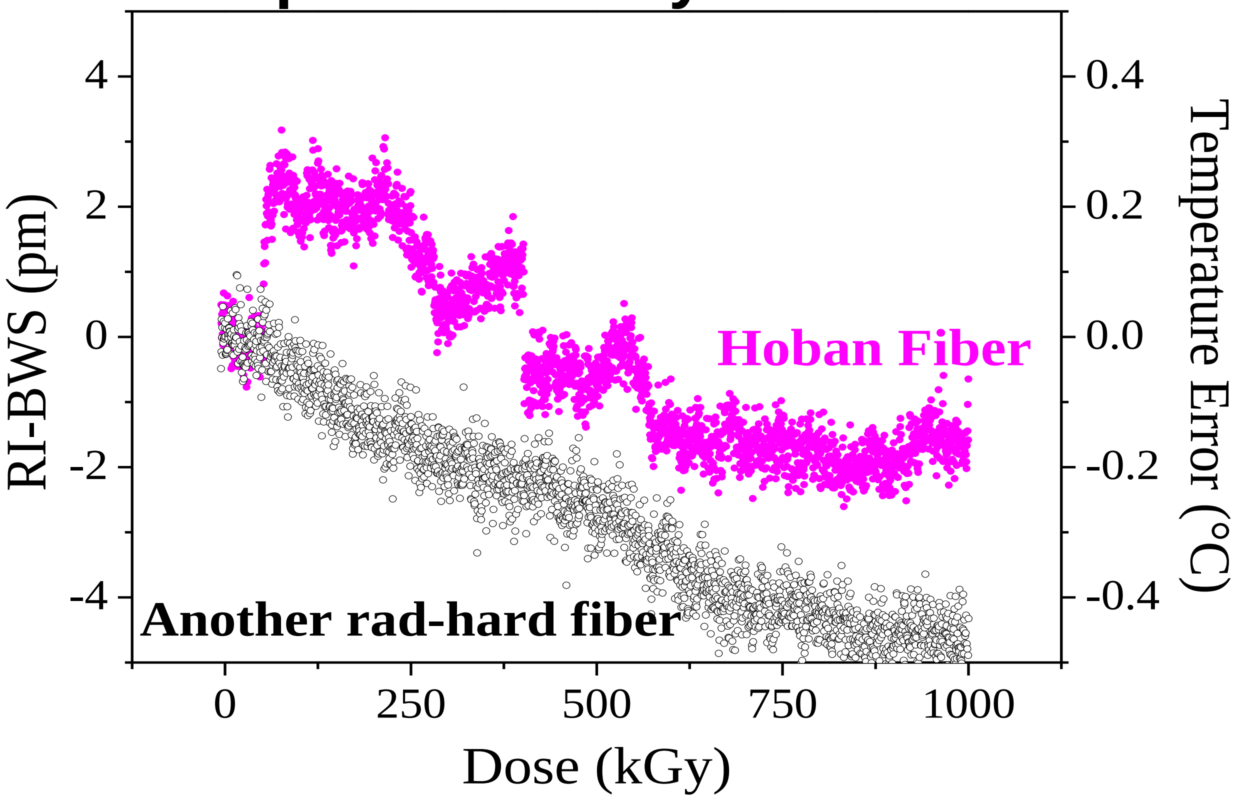
The radiation-response is not affected by inscription parameters within ±0.4°C.

Dose-rate=50 Gy/s
Room temperature

The radiation-resistance of Hoban FBG <u>does not</u> depend on the **Rad-Hard fiber** choice.

Laser pulse width = 150 fs

Laser power density =3.1·10^{13} W/cm²

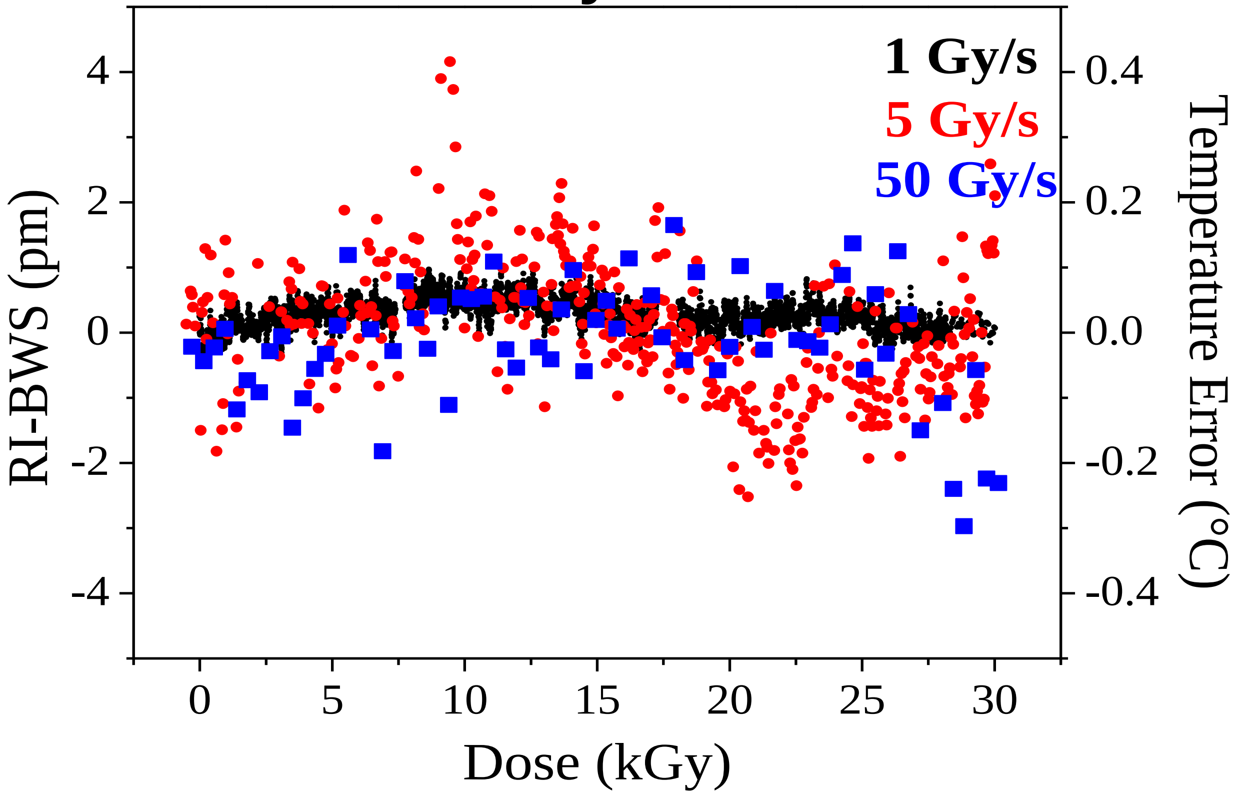


The radiation-response is not significantly affected by the fiber choice within ±0.5°C.

Dose-rate=50 Gy/s
Room temperature

The radiation-resistance of Hoban FBG <u>does not</u> depend on the **dose-rate**.

Laser pulse temporal width = 100 fs
Power density =$3.1 \cdot 10^{13}$ W/cm²



Up to accumulated dose of 30 kGy at RT only fluctuations of about 0.2°C, related to the acquisition.

Contrary to the results on type I FBGs in Ge-doped fibers

The Hoban FBG based sensors are radiation-insensitive under X-rays:

- up to the accumulated dose of **1 MGy**
- for dose-rate between **1 and 50 Gy/s**

within an error of ±0.5°C for temperature sensors
(→error of ±5 pm).

The radiation-resistance is **independent** from

- the inscription-parameters, such as
  - laser pulse temporal width
  - laser power density
- the radiation-resistant fiber type.

Morana et al., Transactions on Nuclear Science, 64, pp. 68-73 (2017).

VI. Hoban FBG response under real irradiation conditions: **γ-rays at higher temperatures**

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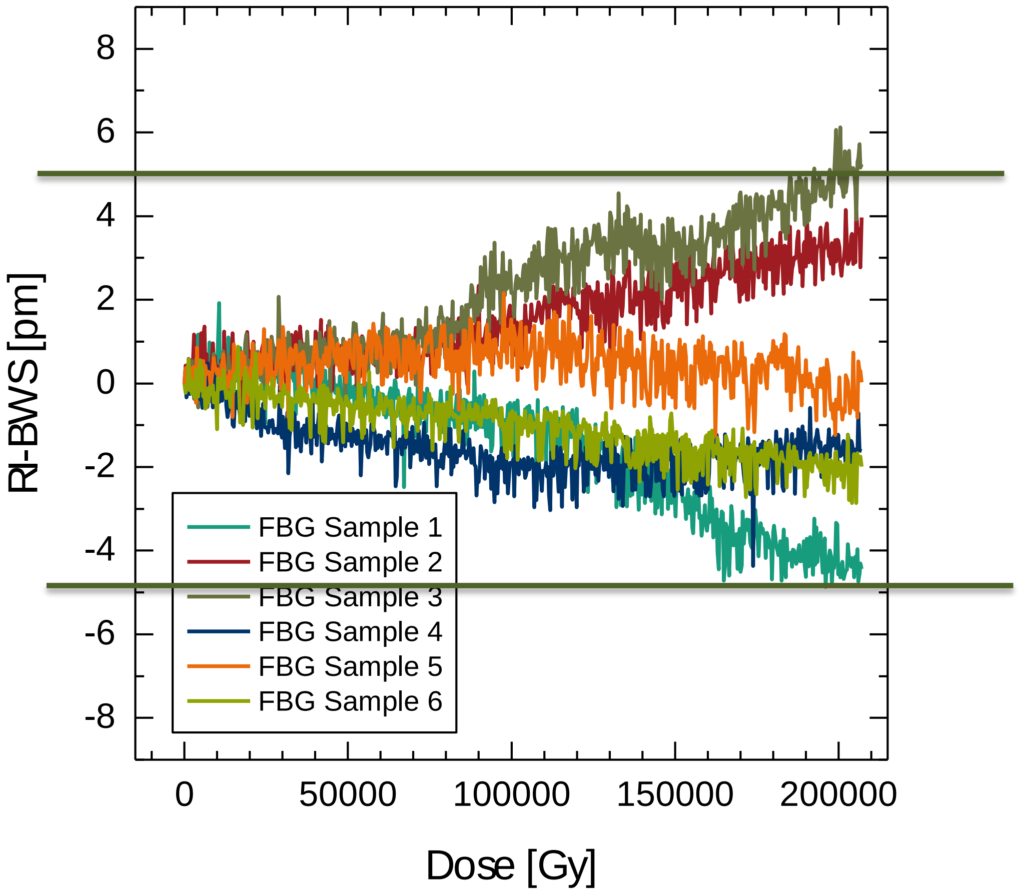
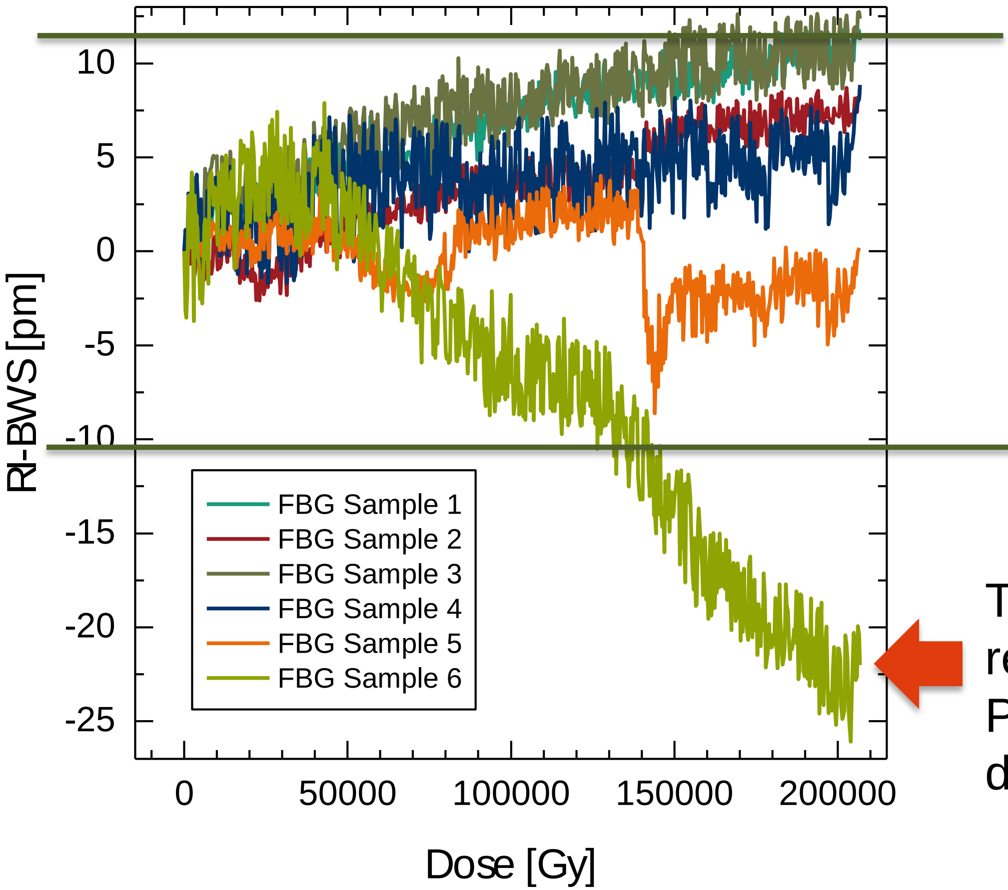
The radiation-resistance of Rad-Hard FBGs was confirmed for γ-irradiation at 100°C...



Up to accumulated dose of 200 kGy at 100°C, the radiation-induced error is only ±0.5°C .

… and also at 350°C



Up to accumulated dose of 200 kGy at 350°C, the radiation-induced error is lower than ±1°C .

This grating showed the same response of a not-treated one. Probably a problem happened during the annealing.

VII. Harsher environments: the nuclear reactor core

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The nuclear reactor core is one of the most harshest environment.

- Gamma-rays :
  - high dose (up to GGy)
  - High dose-rate (between 10^{-2} and 10^{2} Gy/s)
- Neutrons
- High temperatures.

BR2 reactor in SCK·CEN

Temperature: 290°C

Irradiation duration: 22 days

Fast neutron (E>1MeV) flux: (1.5 – 2.5) $\cdot 10^{13}$ n/(cm²·s)

→ **Neutron fluences: 3 and $5 \cdot 10^{19}$ n/cm²**

gamma-dose rate: ~7.2 MGy/h

→ Accumulated gamma-dose: ~3.8 GGy

The temperature error induced on Rad-Hard FBG after a total fast neutron fluence of ~$5 \cdot 10^{19}$ n/cm² and a total γ-dose of 4 GGy is only 4°C.

Fiber core composition	Annealing Temperature (°C)	Pre-irradiation	Initial Reflectivity	Final Reflectivity	RI-BWS (pm)
Fluorine	750	0	8.8%	1.3%	+40
Fluorine	350	3 MGy	62.8%	7.9%	-155
Pure-silica	350	3 MGy			
Pure-silica	750	4 MGy	18.7%	0.4%	+770

Remy et al., Transactions on Nuclear Science, 63(4), pp. 2317-2322 (2016).

VIII. New perspectives: space missions

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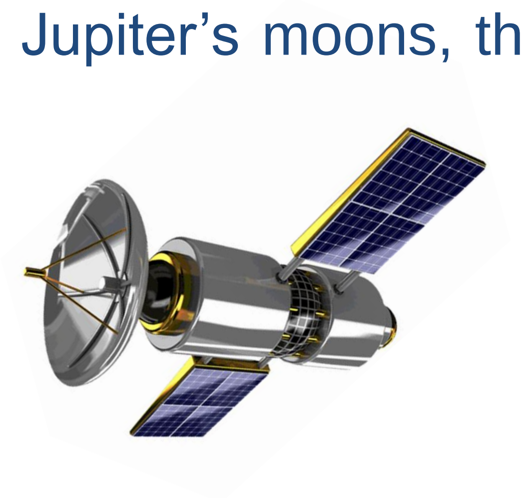
The space is an environment characterized by different radiation constraints.

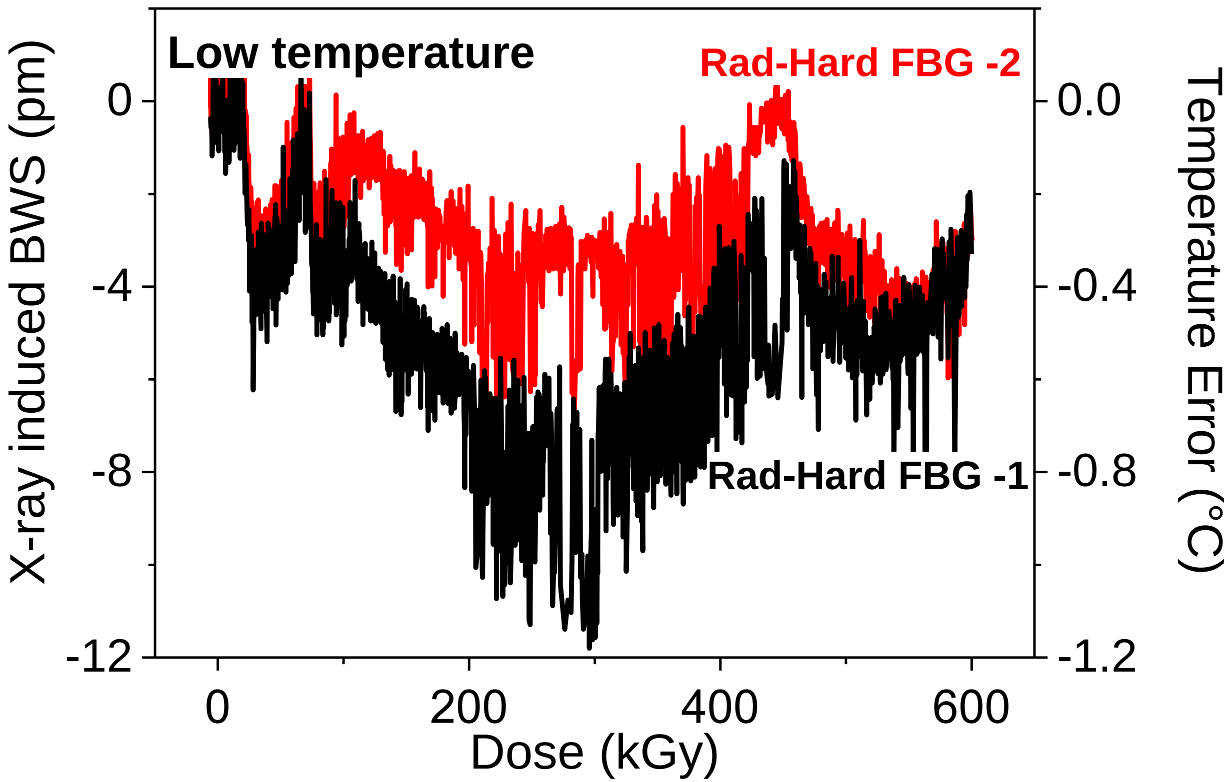
For example for the future Jovian missions to Jupiter's moons, the environment involves:



- Particles:
  - protons,
  - electrons,
  - heavy ions,
- Low equivalent total ionizing dose (of the order of tens of kGy),
- Very low dose-rates (<10-4 Gy/s),
- Large temperature variations, between -200°C and +300°C.

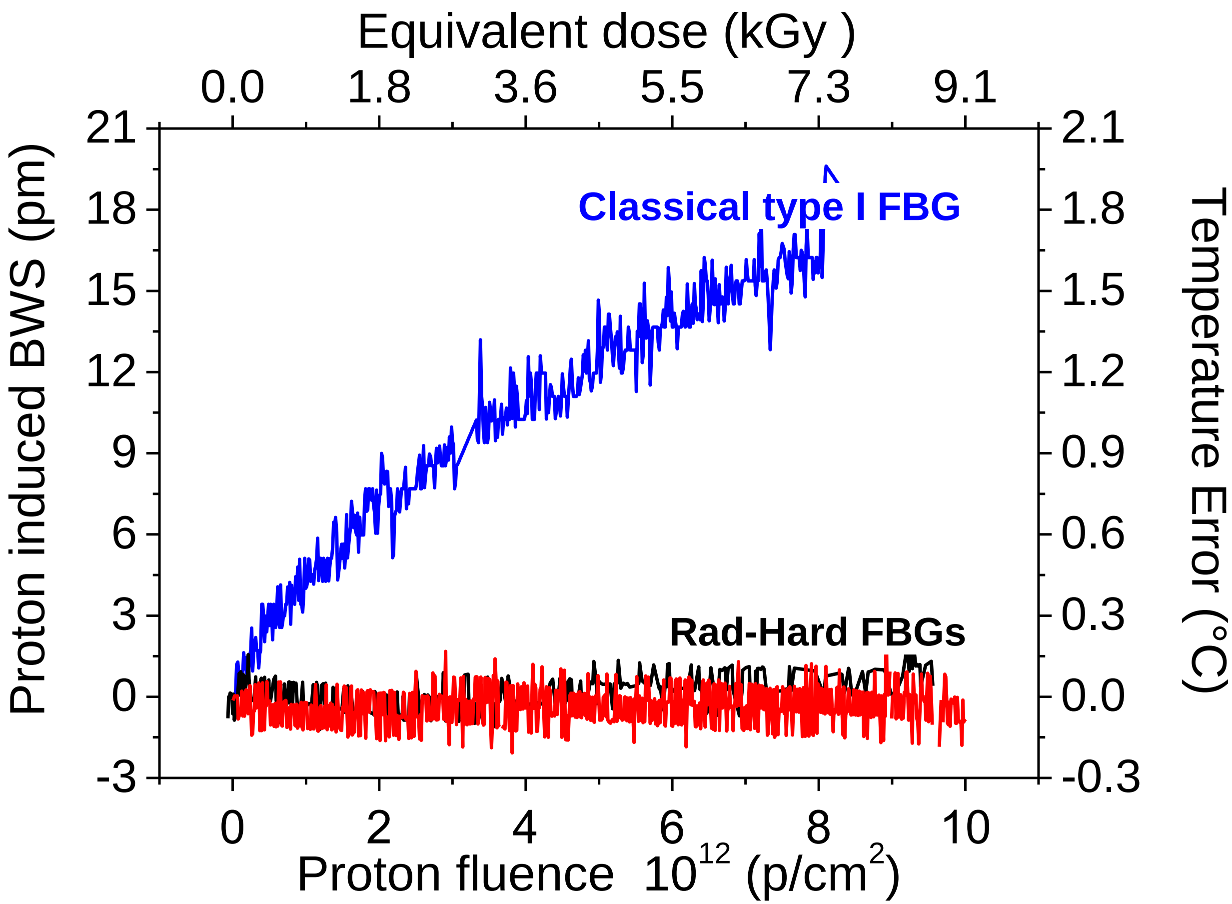
Low temperature effects at -20°C

The temperature error induced by X-rays is still lower than 1°C even for irradiation temperatures as low as -20°C.



Dose-rate=40 Gy/s
Temperature=-20°C

No effect on the FBG response has been detected under proton irradiation.



63 MeV proton beam of the BL2C line at the Proton Irradiation Facility of TRIUMF (Vancouver, Canada).

proton flux $\cong$ $2.96 \cdot 10^{12}$ p/(cm$^2 \cdot$ h)

proton fluence $\cong 10^{13}$ p/cm^2

EQUIVALENT DOSE

dose − rate $\cong$ 2.68 kGy/h

accumulated dose $\cong$ 9 kGy

The Hoban FBG based sensors are good candidate for space missions.

- The temperature error induced by X-rays is still lower than 1°C even for irradiation temperatures as low as -20°C.

- No effect on the FBG response has been detected under proton irradiation, for fluence up to 10^{13} protons/cm², which corresponds to an equivalent dose of 9 kGy(SiO_2).

Morana et al., Photonics and Fiber Technology 2016 (ACOFT, BGPP, NP) OSA (2016), paper JT4A.25.

IX. Conclusions

FINALLY…

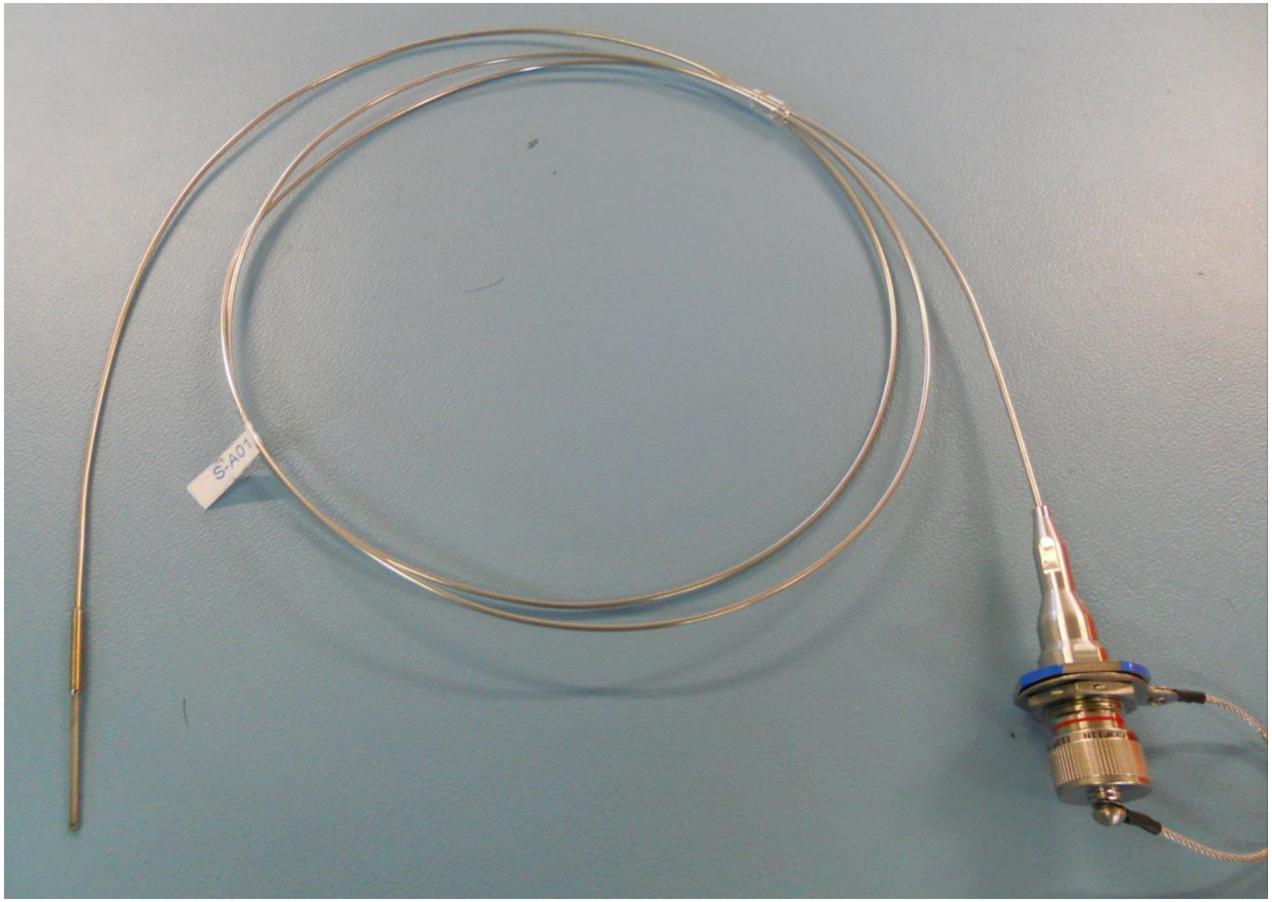
The Hoban FBG based sensors are really suitable for the harsh environments aimed in the project:

- Dose up to 1MGy,
- Temperature up to 350°C.

The radiation-resistance is independent from the inscription-parameters, within the patented ranges.

These sensors are also suitable for space mission (63 MeV protons) and very promising results were also obtained in a nuclear reactor core (~$5 \cdot 10^{19}$ n/cm²).

… the Hoban prototype.



Thank you for your attention

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