Radiation Vulnerability and Hardening of Optical Materials and Optical Systems to MGy Dose Levels

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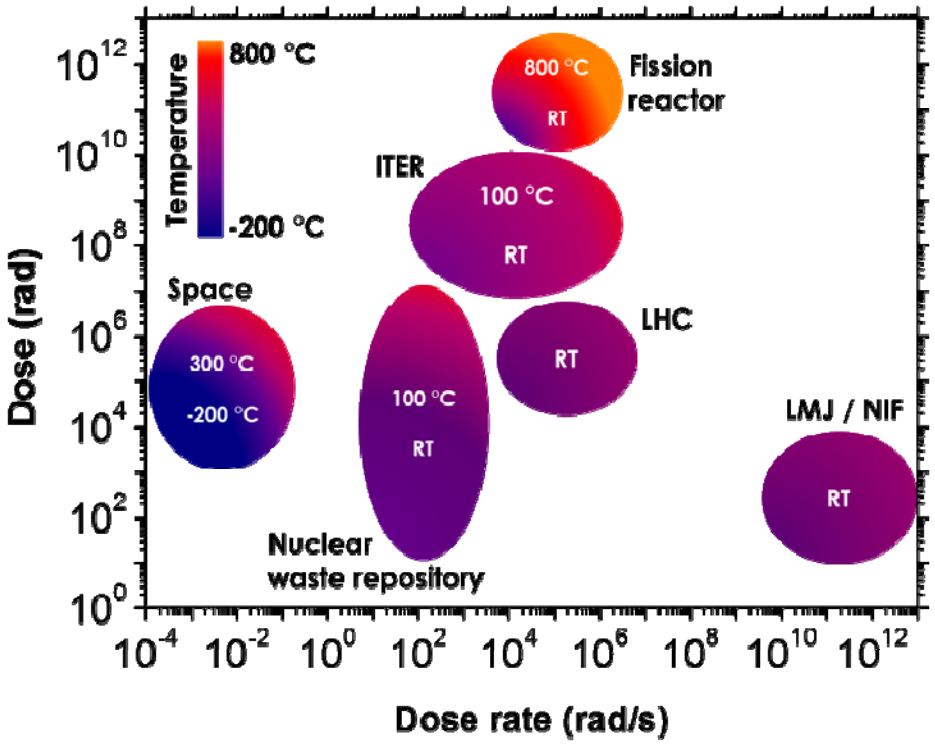
INTRODUCTION

A few words about the research activities of MOPERE group

***M**aterials for **O**ptics, **P**hotonics in **E**xtreme **R**adiation **E**nvironments*

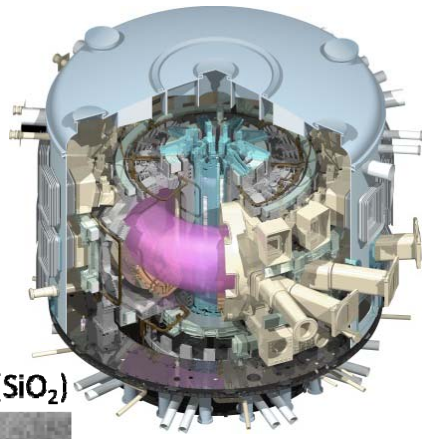


From fiber optic to bulk materials…….

❑ **RESEARCH AXES:**

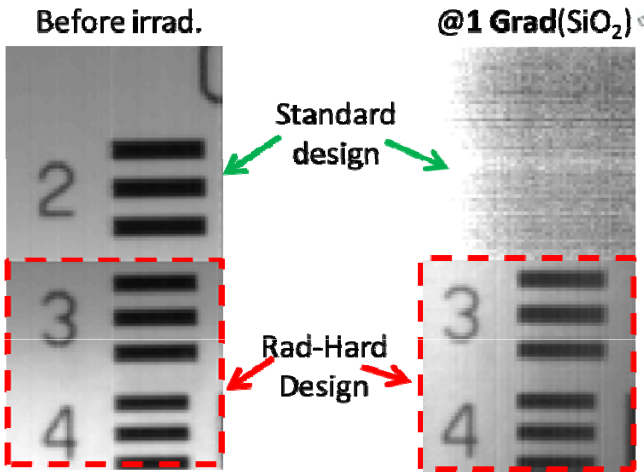
- ✓ Vulnerability & radiation hardening of fibers and fiber-based sensors
- ✓ Experimental study of point defects and their mechanisms in dielectrics
- ✓ Coupled experiments/simulation approach of radiation effects (Joint Research Team CEA-LabHC)
- ✓ **Vulnerability and radiation hardening of CMOS image sensors and Cameras (with CEA DAM and ISAE)**
- ✓ Dosimetry, Nanocomposites, piezoelectric materials, SAW, medical…

Context (1/2): FURHIS project



- ITER remote handling operations require imaging systems
  - ✓ Compact and lightweight
  - ✓ Radiation hard (failure TID >> 1MGy(100 Mrad))
    - ✓ **Gamma radiation only** (plasma OFF)
  - ✓ Color and high definition (≥ 1Mpix)

- Existing CMOS Image Sensors
  - ✓ ISAE studies: operational up to 10MGy



Feasibility study of miniaturized radiation tolerant **MONOCHROME or COLOR optical systems** (OS) at the MGy dose levels

Context (2/2): CAMRAD project

- The CAMRAD aims at developing a new high performance CMOS radiation hard camera technology that can withstand several MGy(SiO_2) of ionizing radiation **without shielding and without significant image quality degradation**.

- Such a technology will significantly benefit the **dismantling and decontamination industries** by enabling the monitoring and inspection of radioactive areas that cannot be observed today.

Dedicated development required for **COLOR optical systems** (OS) to ensure their radiation tolerance at MGy dose levels

EXPECTED RADIATION EFFECTS AT MGy DOSE LEVELS

And how to characterize them?

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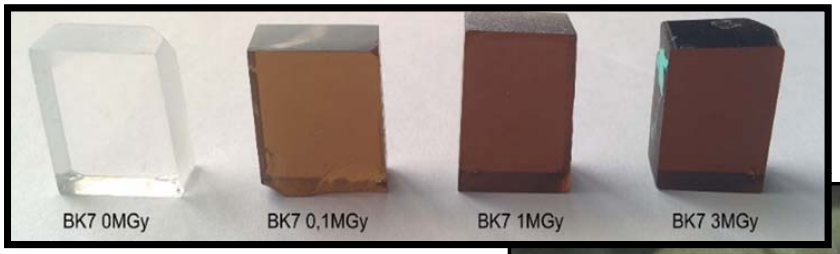
Three degradation mechanisms of bulk glasses at macroscopic scale have been identified under irradiation

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

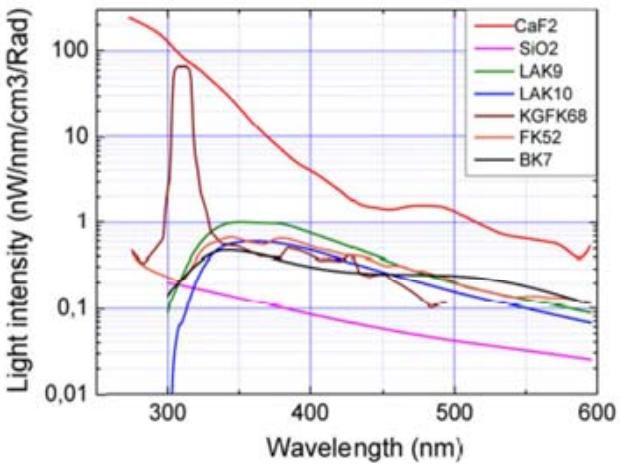


2. **Radiation-Induced Emission (RIE) or scintillation**

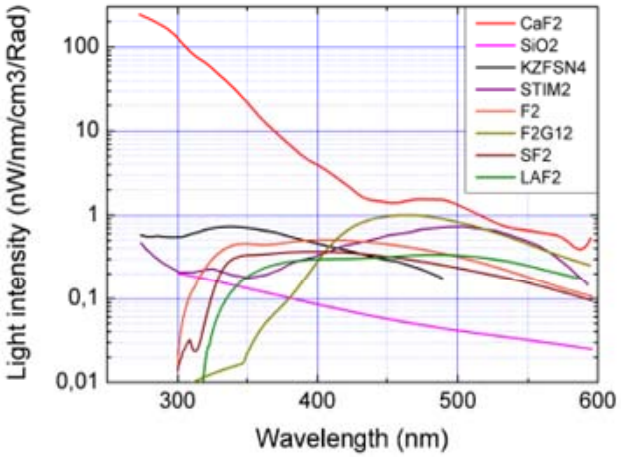
3. **Compaction**

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

RIE or scintillation has been investigated for fusion-related applications (LMJ) associated with high dose rate irradiation constraints



(a)



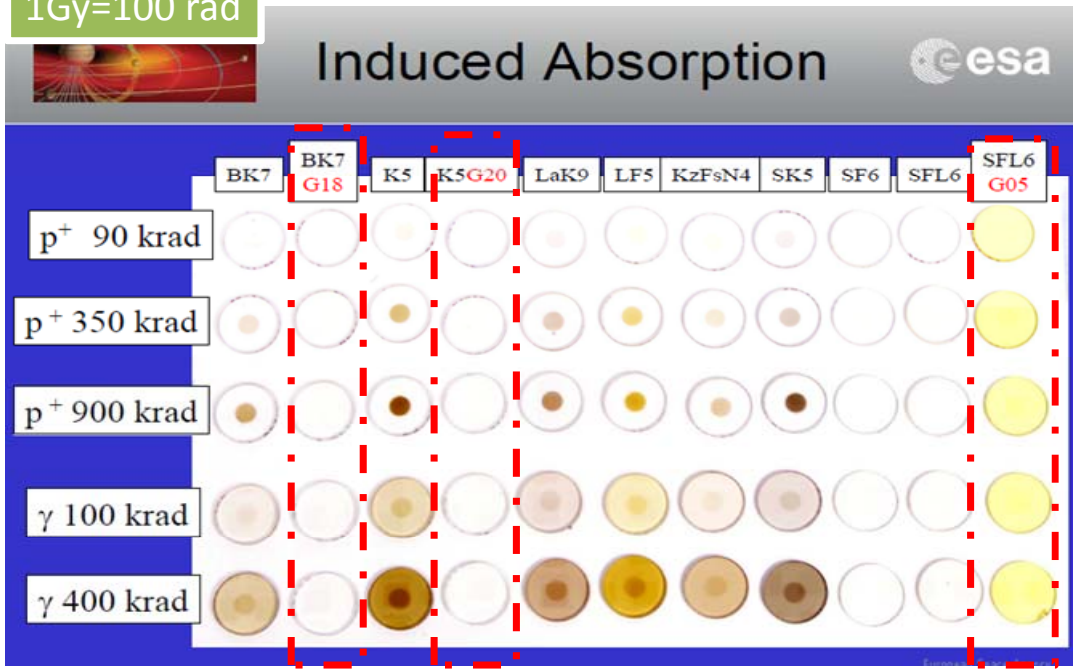
(b)

A. Rousseau ; S. Darbon ; P. Paillet ; S. Girard et al. " Nuclear background effects on plasma diagnostics for megajoule class laser facility ", Proc. SPIE 8850, 2013.

Impact of RIE on the camera performances: The RIE will act as a parasitic signal that will degrade the SNR. Depending on the origin of the light emission and in the case of a color camera, it could differently affect the spectral domain of measurements. RIE could mainly be a problem with radiation-hard optical glasses (due to Ce-doping)

Radiation-induced effects on bulk glasses have been mainly studied for space applications → low range of dose compared to FURHIS or CAMRAD needs (MGy), no data at our doses

1Gy=100 rad



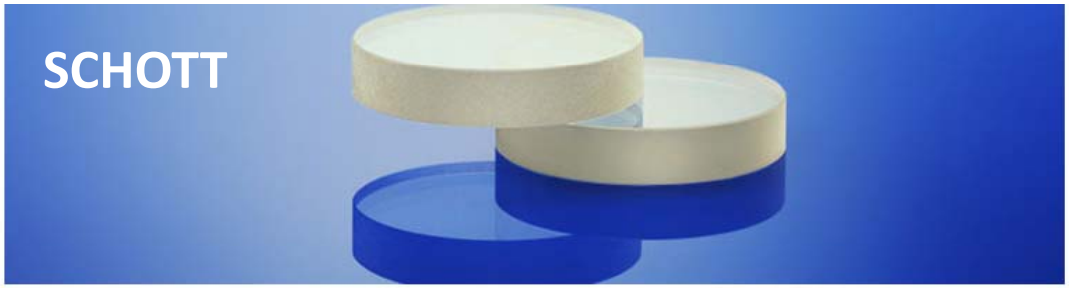
Dominic Doyle,3rd Europa Jupiter System Mission Instrument Workshop, ESA ESTEC January 2010

Except for some Rad Hard (RH) glasses, permanent darkening is observed at low doses in the visible range

Impact of the RIA on the camera performances: by decreasing the transmission efficiency of the optical system, the RIA can lead to a complete loss of the image signal during its transport if the RIA level is sufficient to absorb all travelling photons. A moderate effect can be a strong degradation of the signal to noise ratio of the image.

RIA has been characterized at low doses for space applications through post irradiation measurements

- **Except for Radiation Hard glasses, darkening is observed at low doses in the visible range**



Radiation Resistant Glasses

Product Information | Advantages | Applications | Supply Forms | Technical Details | Downloads

FOR USE IN SURROUNDINGS WITH HIGH IONIZING RADIATION

SCHOTT Advanced Optics offers a variety of radiation resistant glass types with different dispersion properties: BK7G18, LF5G19, LF5G15, K5G20, LAK9G15, F2G12 and SF6G05. These glass-types are suitable for use in surroundings with high radioactivity.

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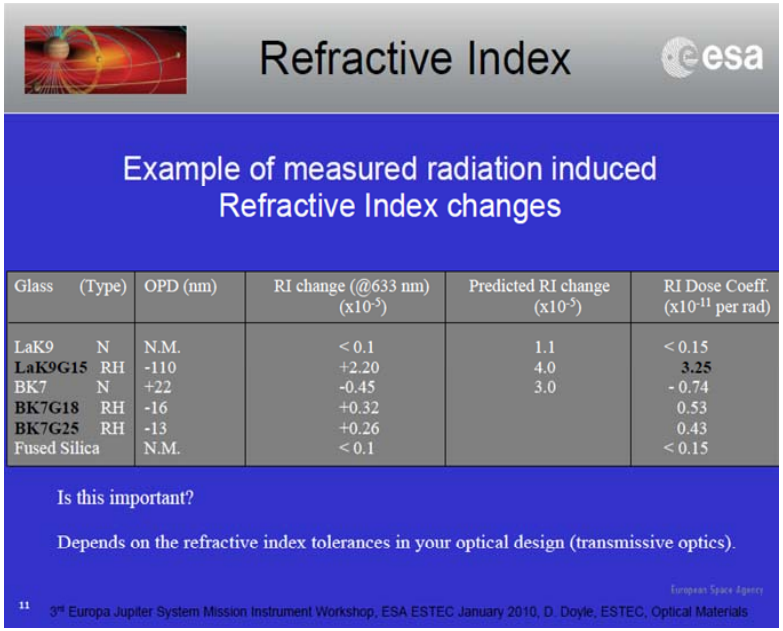
Optical glass can be stabilized against transmittance loss caused by ionizing radiation by adding cerium to the composition. The added cerium changes the intrinsic color of the glass from white to a yellowish tint, while the UV-transmittance edge is shifted to a longer wavelength. Goal is, to optimize the cerium content in order to achieve high stability against radiation while keeping the initial coloring at a minimum level.

The radiation resistance differs with any glass type, whereas it can be extremely high for selected glass types such as BK7G18 and LF5G19.

BK7G18 is identified as one of the most radiation resistant glasses

Are these rad-hard glasses able to operate at MGy (100 Mrad) dose levels? Some post-irradiation data says YES. Is this usual approach correct for our needs?

Amplitude of the RIRIC is not correlated to the one of RIE or RIA ➔ it means that RH glasses could be extremely RIRIC sensitive (not documented yet in literature at MGy dose)



Refractive Index

esa

Example of measured radiation induced Refractive Index changes

Glass	(Type)	OPD (nm)	RI change (@633 nm) ($x10^{-5}$)	Predicted RI change ($x10^{-5}$)	RI Dose Coeff. ($x10^{-11}$ per rad)
LaK9	N	N.M.	< 0.1	1.1	< 0.15
LaK9G15	RH	-110	+2.20	4.0	**3.25**
BK7	N	+22	-0.45	3.0	- 0.74
BK7G18	RH	-16	+0.32		0.53
BK7G25	RH	-13	+0.26		0.43
Fused Silica		N.M.	< 0.1		< 0.15

Is this important?

Depends on the refractive index tolerances in your optical design (transmissive optics).

11 3rd Europa Jupiter System Mission Instrument Workshop, ESA ESTEC January 2010, D. Doyle, ESTEC, Optical Materials

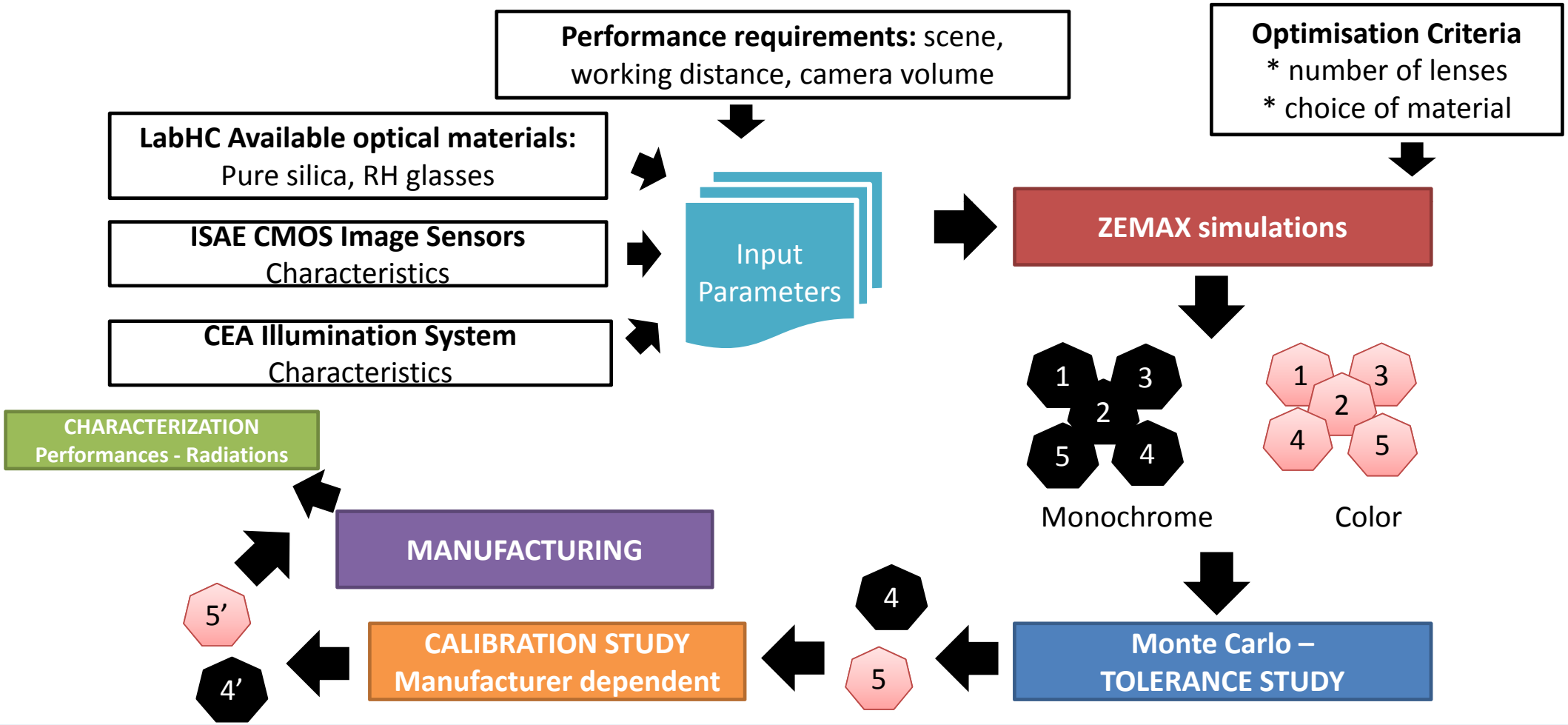
Dominic Doyle, 3rd Europa Jupiter System Mission Instrument Workshop, ESA ESTEC January 2010

RIRIC is one of the aspect that has to be investigated during FURHIS

- Measurements of RIRIC (ABBEMAT refractometer)
- Tolerance study (ZEMAX simulations)

Impact of RIRIC on the camera performances: The RIE will act as a defocusing that can strongly degrade the image quality

Strategy for radiation hardened color and monochrome OS design and manufacturing



EXPERIMENTAL PROCEDURE AND RESULTS

Radiation-Induced Attenuation in Bulk Optics

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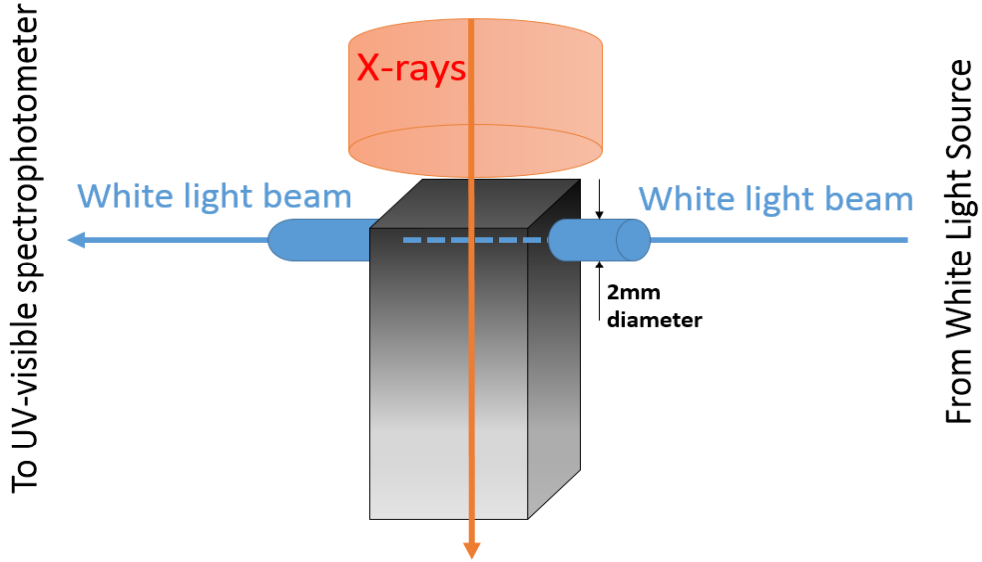
We developed an home-made setup allowing to record the RIA levels during and after irradiation

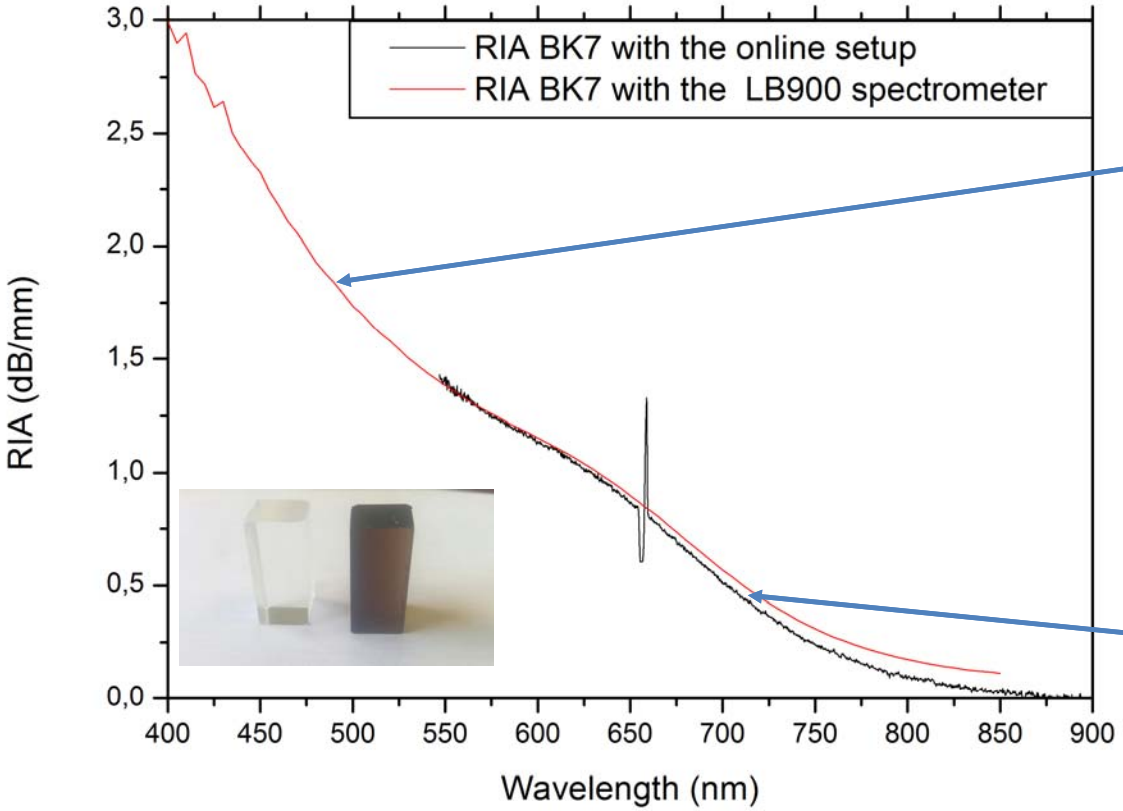


- **Dose rate:** 1mGy/s to >100Gy/s
- **Dose** up to >10MGy (30% uncertainty)
- **T irradiation:** RT – 300°C
- **Spectral range:** 400- 1100nm

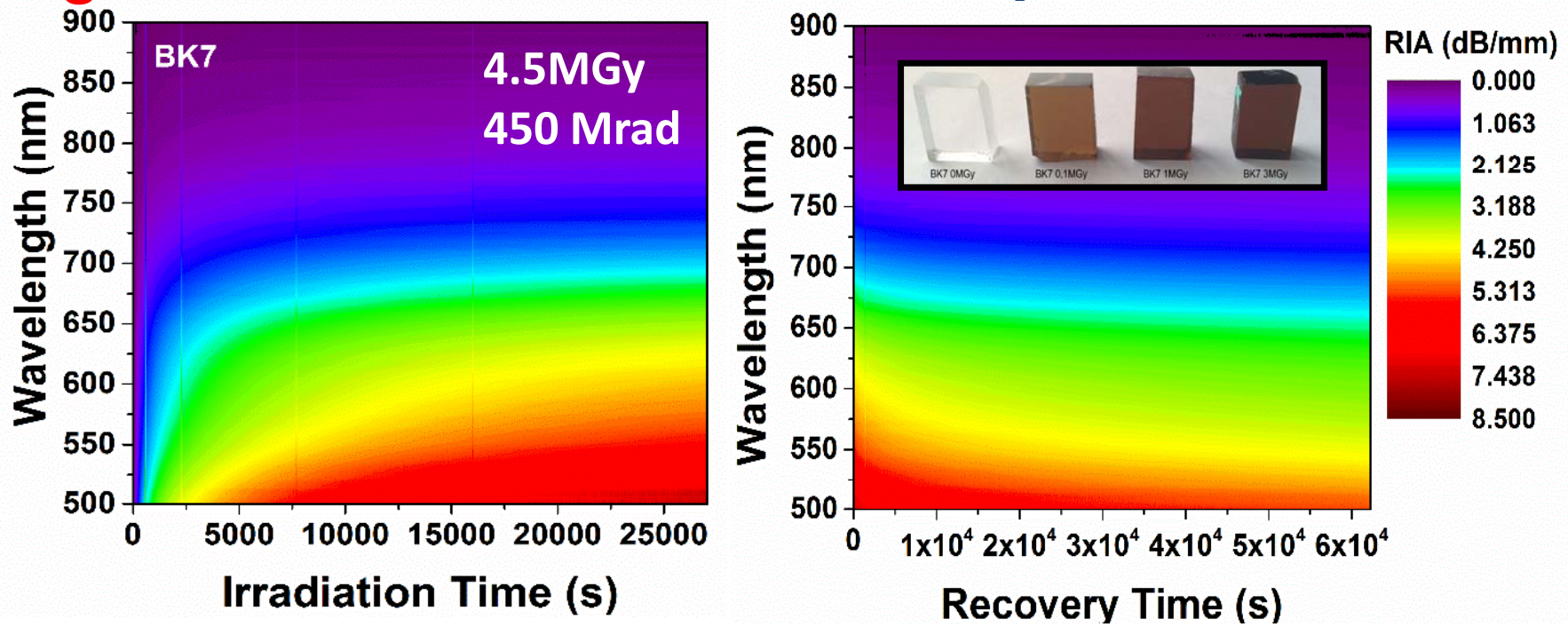
By this way, both the contributions of room-temperature stable and unstable defects can be characterized: 2D map of RIA vs D, λ

Validation of the new setup

- Comparison between online RIA measurements (done 2h after end of X-rays) and post mortem measurements with spectrophotometer

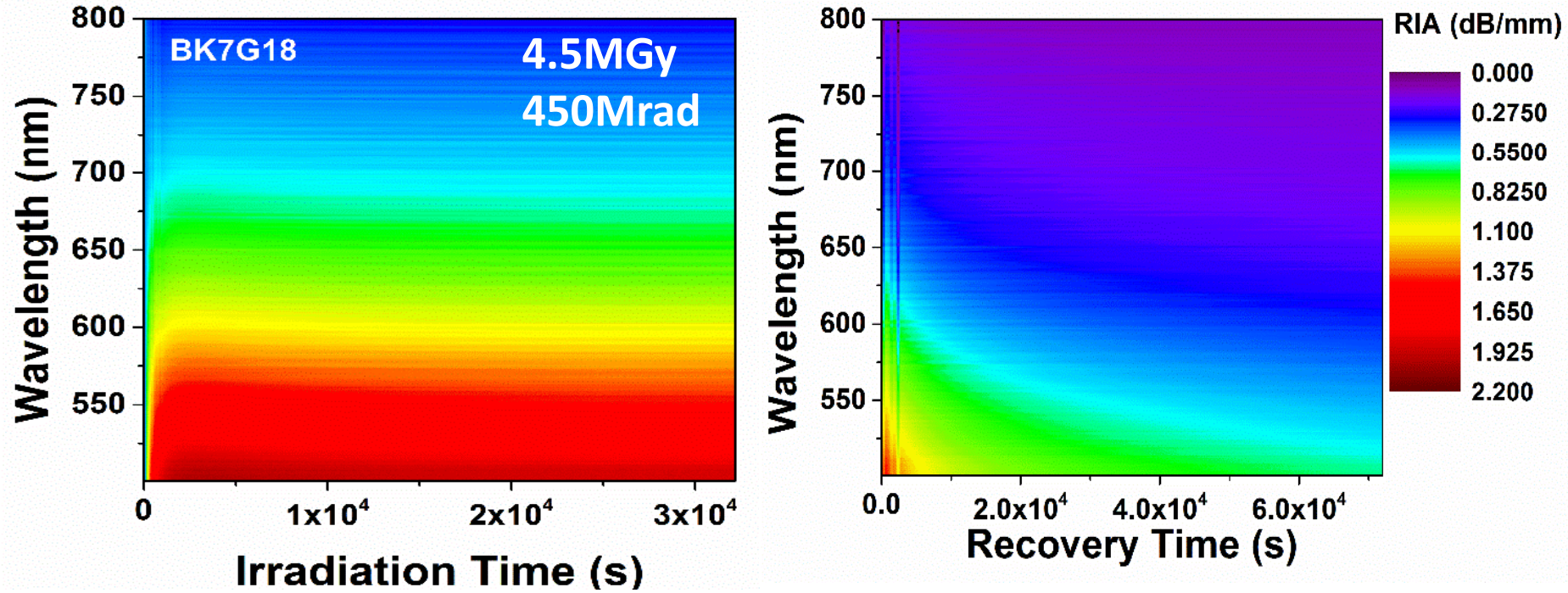


We validate the setup and used it to compare the response of BK7 glass and its rad-hard counterpart BK7G18



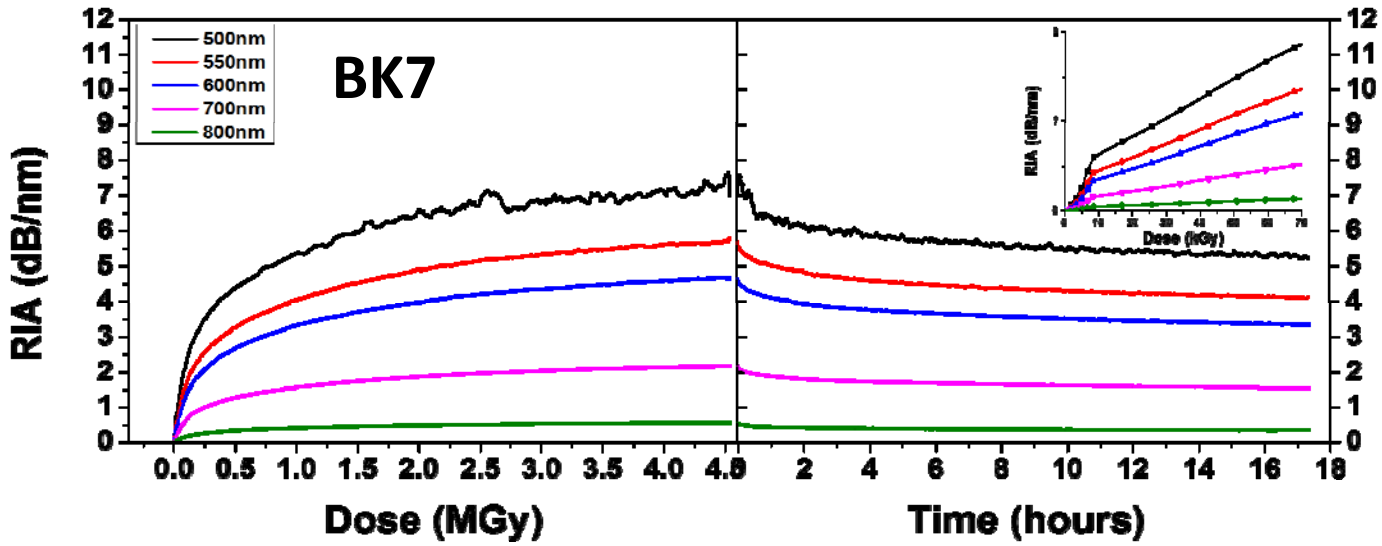
- **BK7 presents high RIA levels** (up to 8 dB/mm), slow RIA recovery after irradiation
- **Usual Post irradiation RIA measurements slightly underestimate BK7 vulnerability**

We validate the setup and used it to compare the response of BK7 glass and its rad-hard counterpart BK7G18



- **BK7G18 presents high RIA levels** too (>2dB/mm), fast RIA recovery after irradiation
- **Usual Post irradiation RIA totally fails to estimate this glass RIA level**

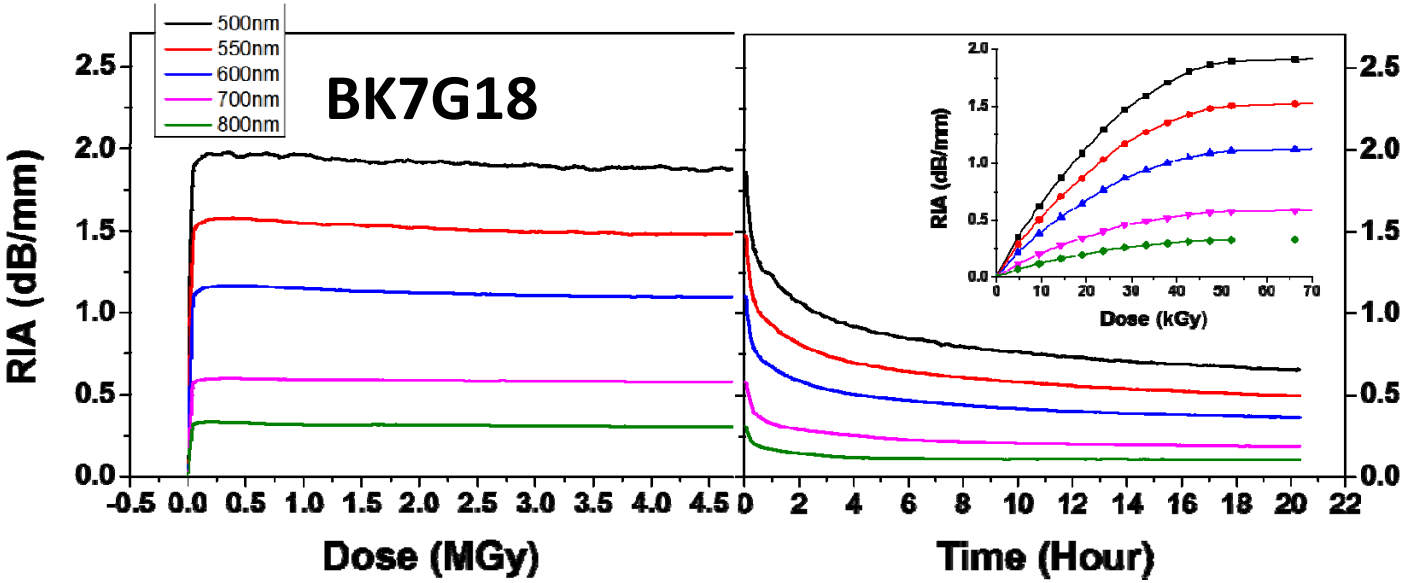
From such maps, RIA spectral and time(dose) dependences can be extracted and analyzed



✓ Classic power law dependence of RIA with dose ➔ results from the competition between defect generation and bleaching during irradiation

❑ **By performing a systematic study of RIA vs Dose, Dose Rate, T, λ ➔ models can be applied to extrapolate RIA levels for a large variety of environments**

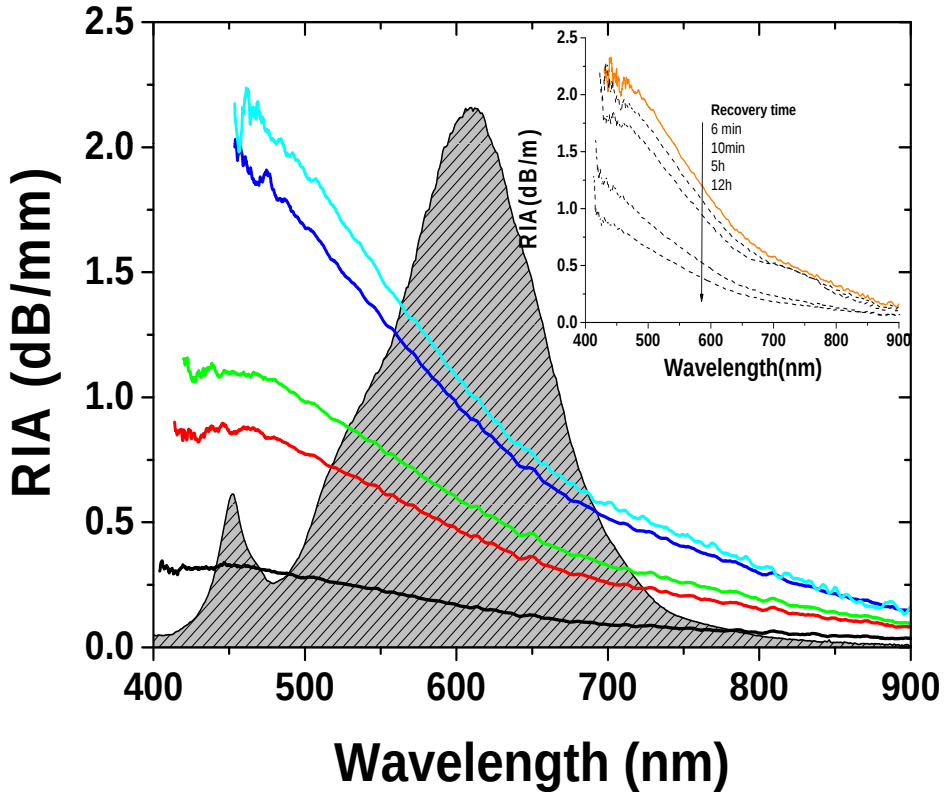
From such maps, RIA spectral and time(dose) dependences can be extracted and analyzed



✓ Such kinetics are consistent with the highly efficient generation of metastable defects characterized by a low stability at RT

❑ **When irradiation starts, numerous defects are created, then the competition between creation and bleaching processes results in a RIA decrease at higher doses (times) as it was observed in some radiation-hardened pure silica fibers (STHs)**

From such maps, RIA spectral and time(dose) dependences can be extracted and analyzed

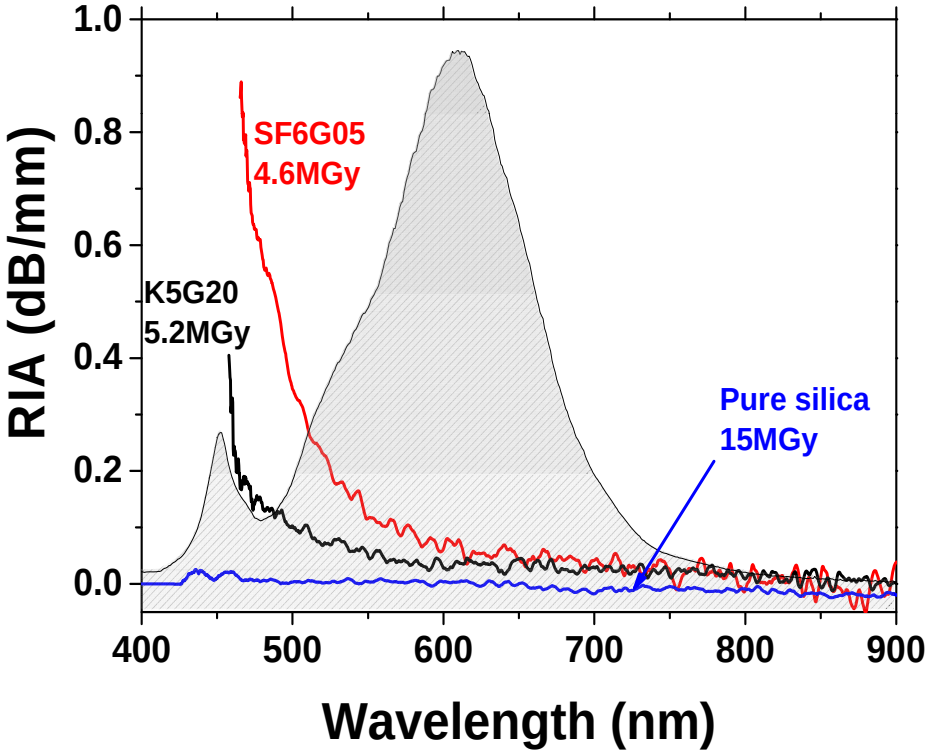


- no clear absorption bands can be detected in the visible domain, with no clear signature of STH-related defects even if bands at around 450nm in BK7G18 seems discernable.

- **As shown by the comparison with a rad-hard LED output, most of the light will suffer from RIA level of 0.1 dB/mm (10dB for 1cm thick OS)**

Is this transient RIA caused by the Ce-doping of the glass?

No, tests on K5G20, SF6G05 glasses confirm the radiation hardness of other tested rad-hard Ce-doped glasses



- With an appropriate choice of rad-hard glasses and pure silica, systems with materials having RIA <0.3 dB/mm (3dB/cm at λ>500nm) can be achieved

- **For the application, blue part of the spectrum will be the most affected ➔ hardening by system: increase the number of blue LEDs**

EXPERIMENTAL PROCEDURE AND RESULTS

Radiation-Induced Refractive-Index Change

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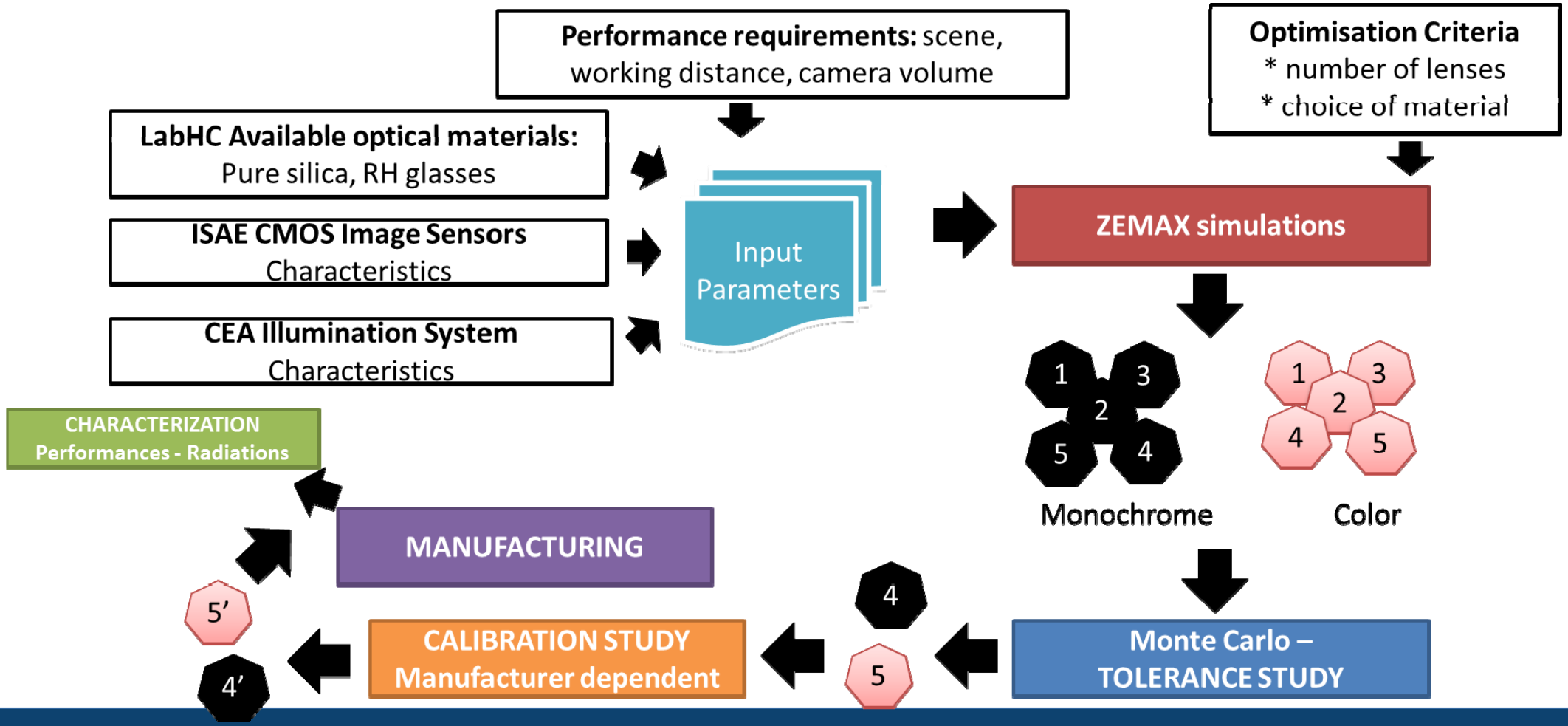
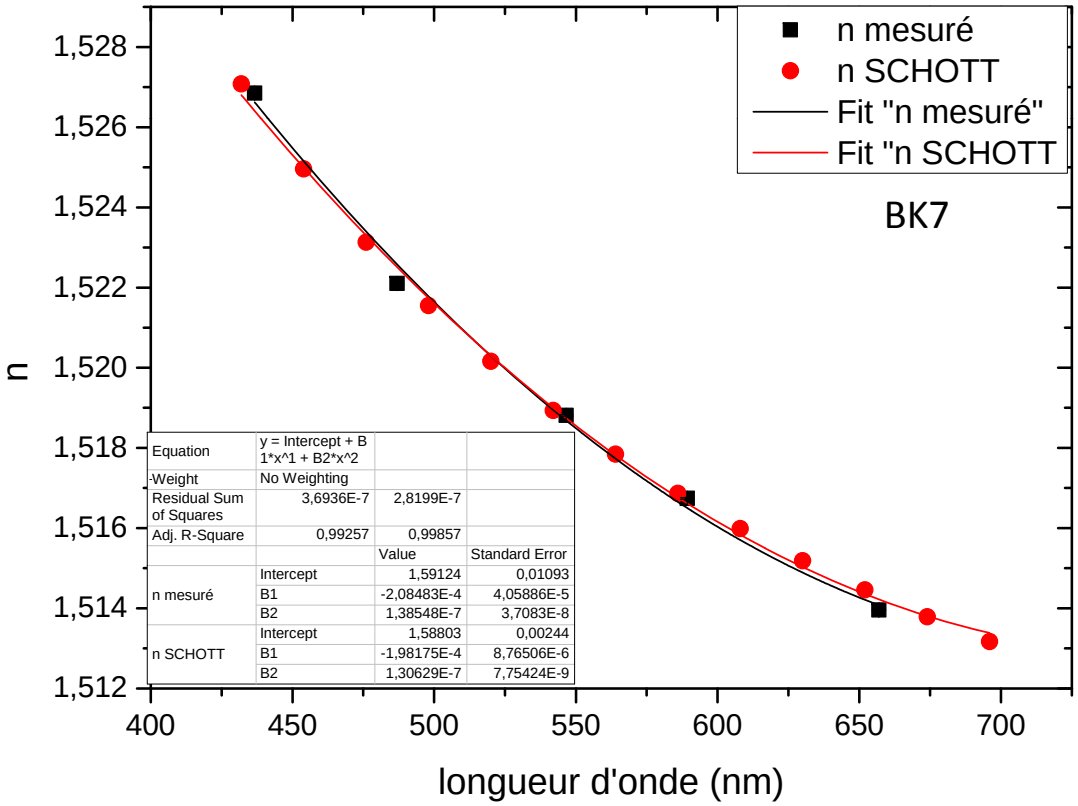
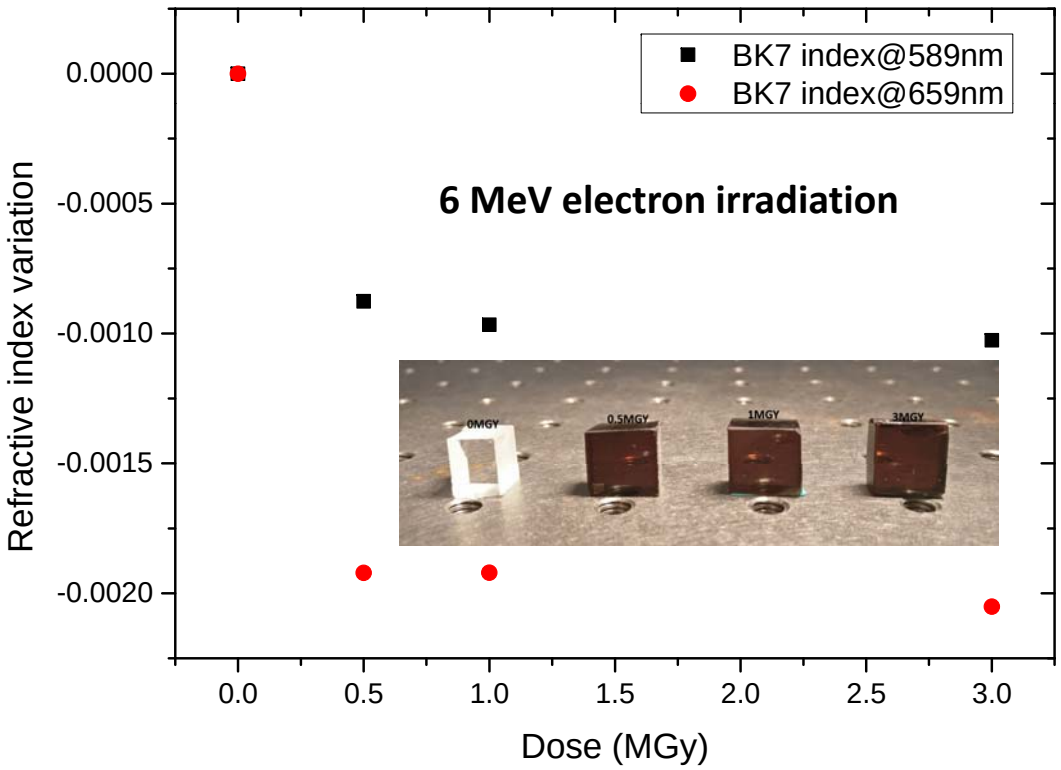
Strategy for radiation hardened color and monochrome OS design and manufacturing



RI measurements post-mortem: a new setup is under evaluation, precision is of about $5x10^{-5}$ for the RI

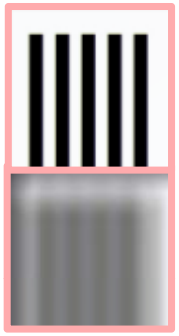


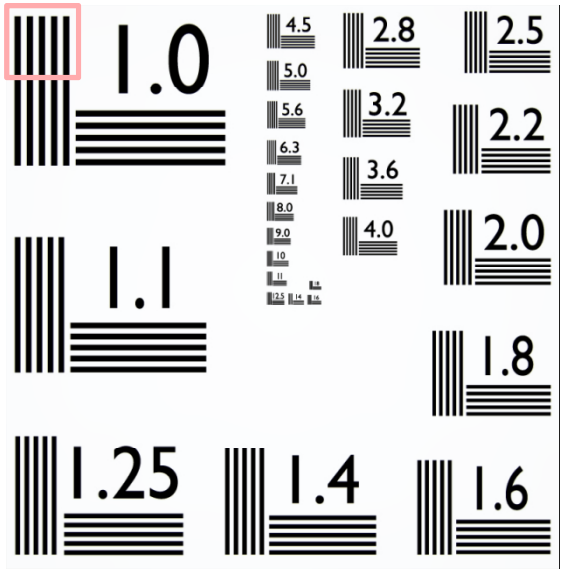
Equation	y = Intercept + B 1*x^1 + B2*x^2		
Weight	No Weighting		
Residual Sum of Squares	3,6936E-7	2,8199E-7	
Adj. R-Square	0,99257	0,99857	
		Value	Standard Error
n mesuré	Intercept	1,59124	0,01093
	B1	-2,08483E-4	4,05886E-5
	B2	1,38548E-7	3,7083E-8
n SCHOTT	Intercept	1,58803	0,00244
	B1	-1,98175E-4	8,76506E-6
	B2	1,30629E-7	7,75424E-9

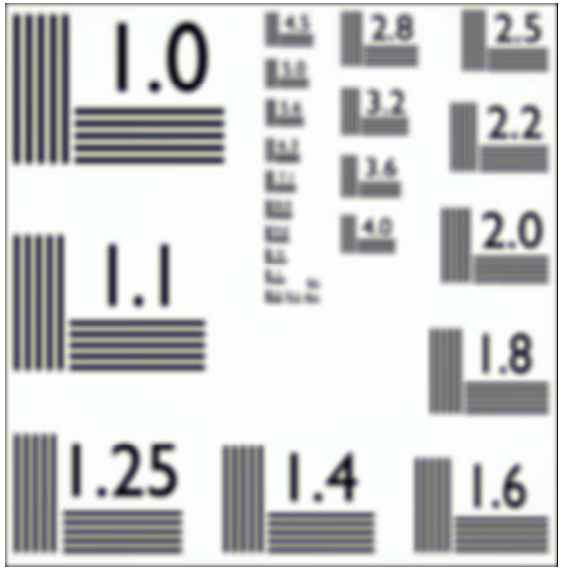


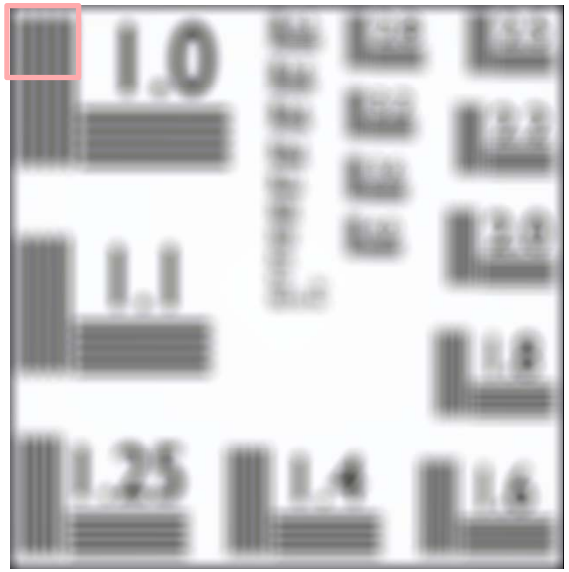
RIRIC impact: *estimation through simulations (1/2)*

- Refractive index change => defocus => image blurring
- To which extent ?



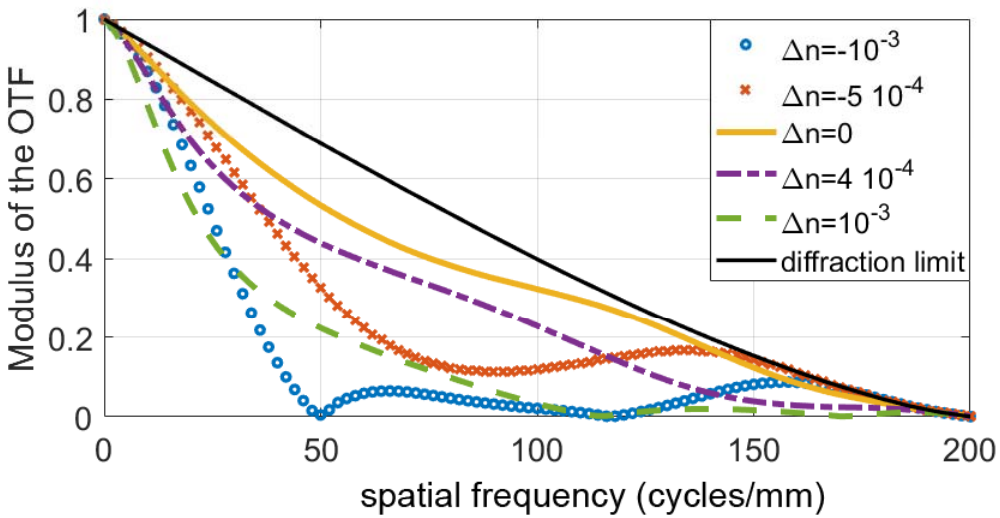


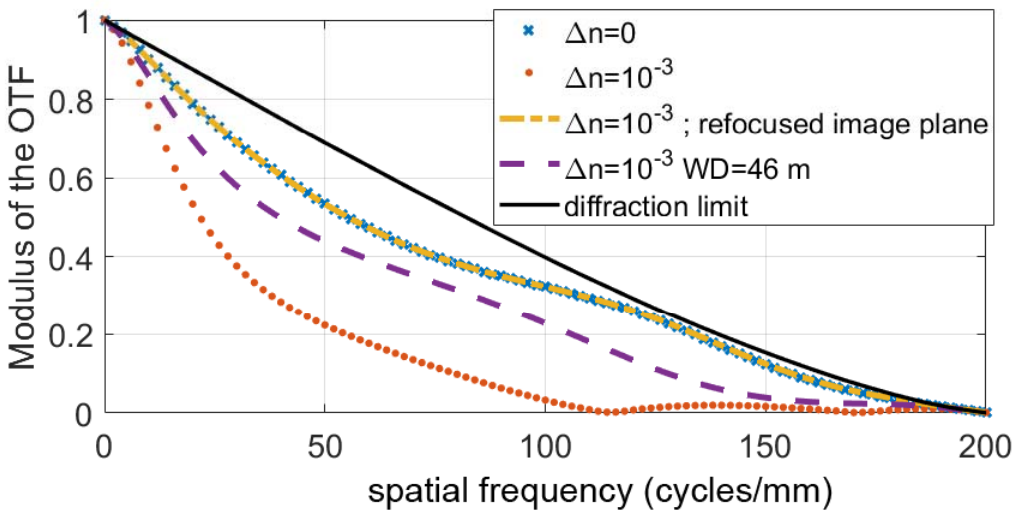




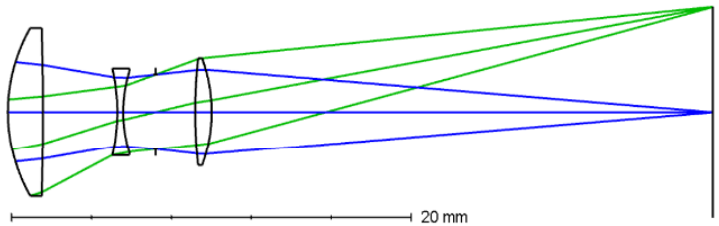
RIRIC impact: *estimation through simulations (2/2)*

- Effect on the MTF for a single Silica lens
  - Refocusing brings the MTF back almost at its previous level



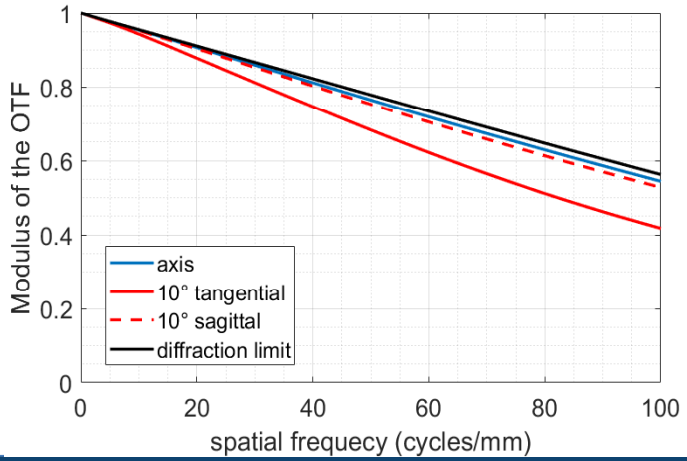


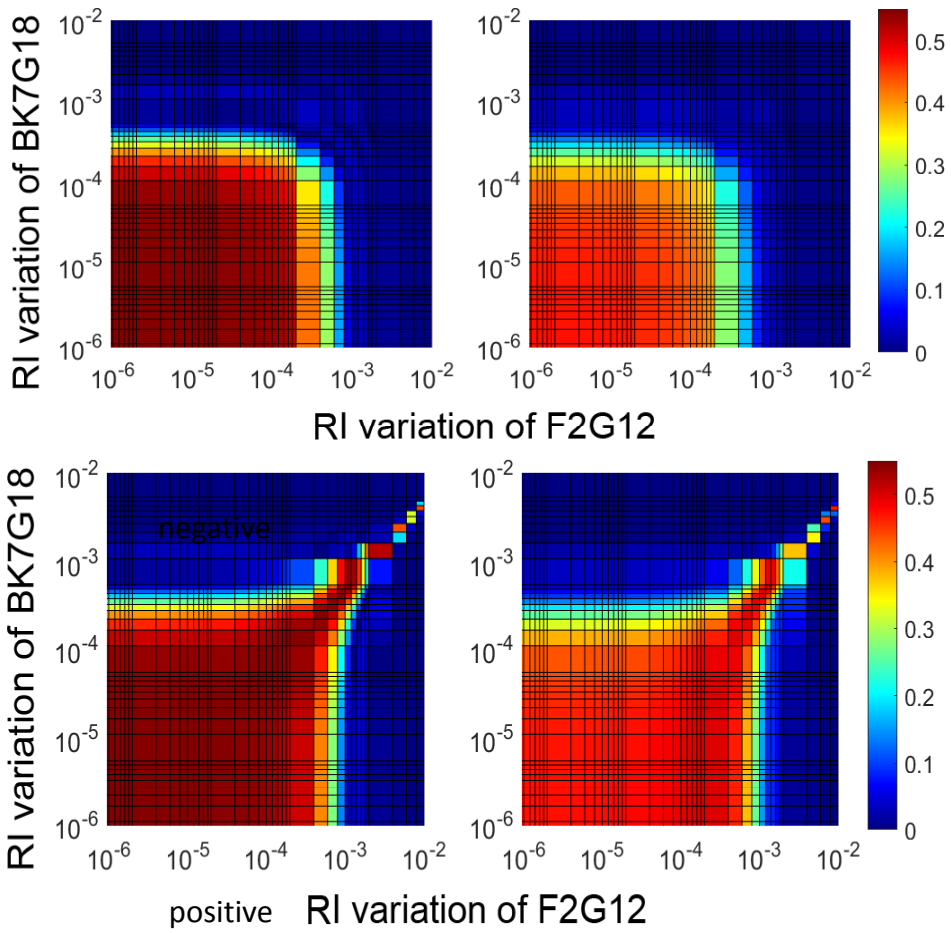
Mitigation solutions under investigation: *Design of self-compensating optical systems*



Effect on the MTF for a dummy system

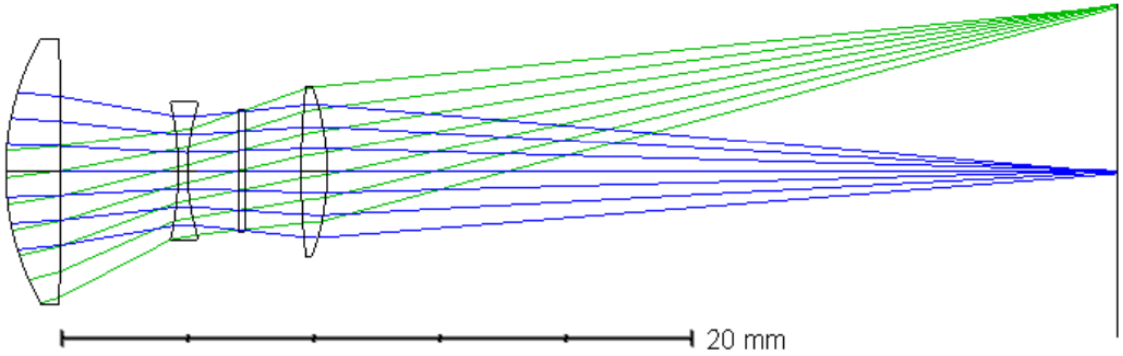
– BK7G18 and F2G12

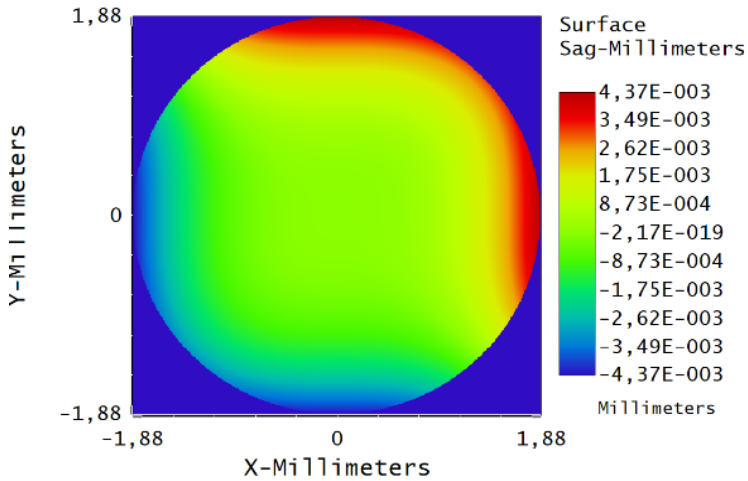




Mitigation solutions under investigation: *Wavefront Coding (1/2)*

- Adding a phase mask in the optical system allows increasing its robustness to RIRIC at the cost of a degradation of initial performances
  - Its thickness is $t(x,y) = t(0,0) + \frac{\lambda\alpha}{2\pi n}(x^3 + y^3)$



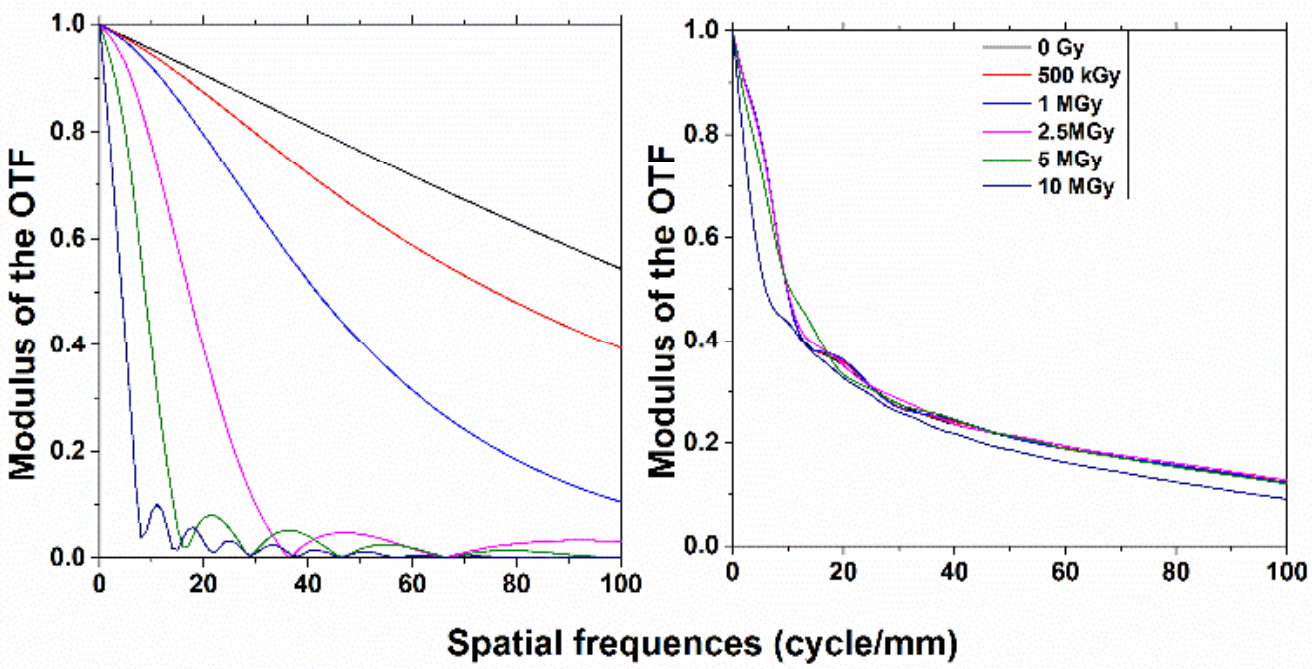


Mitigation solutions under investigation: *Wavefront Coding (2/2)*

- Adding a phase mask in the optical system allows increasing its robustness to RIRIC at the cost of a degradation of initial performances

RIRIC values for the assumption of linearity between Dose and Δn:

- $\Delta n_{F2G12} = 0.2 \cdot 10 - 9$ Gy^{-1}
- $\Delta n_{Silica} = 0{,}1 \cdot 10^{-9}$ Gy^{-1}
- $\Delta n_{BK7G18} = 0{,}53 \cdot 10^{-9}$ Gy^{-1}



Conclusions/Perspectives

- Various tools at LabHC to investigate radiation effects on glass (RIE, RIL, RIRIC) through experiments and simulations
- 2 PhD students (Timothé ALLANCHE and Cyprien MULLER)
- Many irradiation opportunities through collaborations: X-rays, gamma-ray, protons, ions, neutrons, electrons over 2018

➢ **We are interested in extending the covered range of doses and materials with the goal to built a, open-access knowledge on radiation effects on bulk optics and continue to develop this activity in Saint-Etienne on the long-term.**

Acknowledgements

FURHIS project: V. Goiffon, P. Paillet, M. Van Uffelen, L. Mont-Casellas, F. Corbière, S. Rolando, S. Rizzolo, P. Magnan, O. Duhamel, C. Marcandella, M. Gaillardin, T. Allanche, C. Muller, T. Lépine, A. Boukenter, R. Scott, W. De Cock

CAMRAD project: V. Goiffon, P. Paillet, J-R. Macé, M. Osmond, P. Burnichon, S. Plumeri, J-P. Baudu, A. Boukenter, C. Muller, T. Allanche, P. Magnan, S. Rizzolo, F. Corbière, R. Molina, Y. Ouerdane, T. Lépine, R. Clerc.