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CAMRAD: Development of a Multi-Megagray Radiation Hard CMOS Camera for Dismantling Operations

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Abstract: The CAMRAD research and development project aims at developing a new high performance CMOS radiation hard camera technology that can withstand several MGy(SiO₂) of ionizing radiation without shielding and without significant image quality degradation. Such a technology will significantly benefit to the dismantling and decontamination industries by enabling the monitoring and inspection of radioactive areas that cannot be observed today. This paper presents the overall project as well as the results of the technology exploration phase aiming at selecting the best materials, designs and hardening techniques to reach the ambitious goal of CAMRAD.

KEYWORDS: *Camera, Radiation Hard, Ionizing Radiation, Imaging System, CMOS Image Sensor, Optics, Optical System, Rad-Hard Glass, LED, Monitoring, Inspection*

Introduction

Dismantling and decontamination of shutdown nuclear facilities require the use of radiation resistant imaging systems to monitor the radioactive wastes, remote handling operations, to inspect reactors, plants or laboratories and to control dismantling robots. Tube based cameras currently offer the highest radiation hardness but they are fragile, bulky and limited in terms of performance and image resolution. Commercially available off-the-shelf (COTS) radiation tolerant camera based on solid-state image sensors, such as Charge Injection Devices (CID) or Complementary Metal Oxide Semiconductor (CMOS) Image Sensors (CIS), are limited to a maximum Total Ionizing Dose (TID) of 100 kGy(SiO₂) when no shielding and no thermal annealing techniques are used to extend their lifetime (as illustrated in Figure 1).

In this work the CAMRAD research and development project is presented: it aims at developing a new high performance CMOS radiation hard camera technology that can withstand several MGy(SiO₂) of ionizing radiation (i.e. several hundreds of Mrad(SiO₂)). CAMRAD is supported by Andra (French National Radioactive Waste Management Agency) under the "Investing in the Future" program ("*Programme d'Investissement d'Avenir (PIA)*").

With its higher radiation hardness level, its lightweight and small size, such a technology could potentially change the way dismantling operations are done by allowing the inspection of radioactive areas that cannot be observed today. This technology will reduce the frequency of replacement of imaging systems and it will have a direct positive impact on costs as well as on staff safety and security in these facilities.

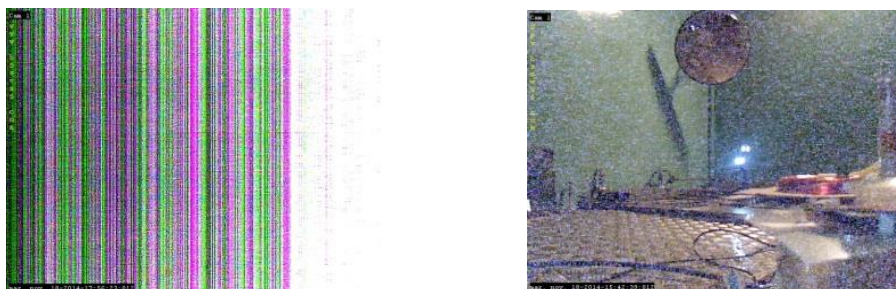


Figure 1 : Typical failure and image degradation observed on COTS camera at low TID.

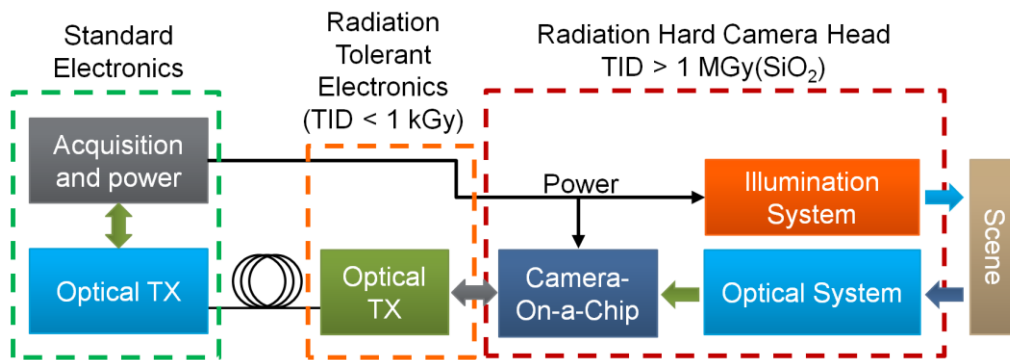


Figure 2 : CAMRAD camera prototype synoptic diagram.

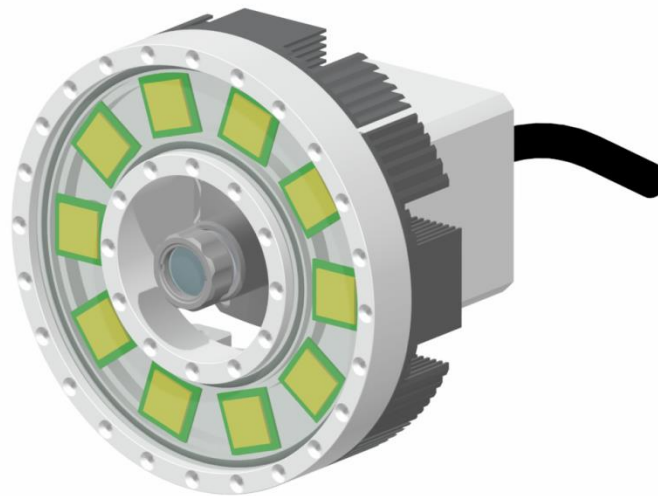


Figure 3 : CAMRAD camera prototype preliminary design.

Project and Technology Overview

An overview of the CAMRAD imaging system is presented in Figure 2 and a preliminary design illustration of its camera head is displayed in Figure 3. The radiation hardened camera head includes an illumination system, an optical system and a camera-on-a-chip integrated circuit that can withstand MGy doses. To communicate with the electronic chip, especially for data transmission from the head to the acquisition computer, a radiation tolerant electro-optical transceiver link based on a radiation hardened optical fiber is placed several meters away from the camera head. By placing the electro-optical conversion module far from radioactive area to observe, the radiation constraint is lowered down to a few kGy(SiO₂). At such TID level, the electro-optical conversion system can be designed based on existing solutions and no particular dedicated technology will be developed during the project. The selected optical fiber for this link is also considered radiation hard at this TID level [1]. Finally, the other optical transceiver and the acquisition system (left-hand side of Figure 2) are located in a radiation free zone (typically at the end of an optical link longer than 100 m) and are designed with conventional commercial electronics.

Hence, the main challenge of this project lays in the development of the Multi-MGy radiation hard camera head. The first originality of this project consists in integrating all the camera head electronics on a single chip and to harden by design the entire integrated circuit as proposed in [2], [3]. Indeed, typical radiation hardened cameras based on solid-state image sensors make use of several integrated circuits in the camera head and most of them are not hardened against MGy TID levels. The key elements integrated on the CAMRAD radiation hardened camera-on-a-chip are illustrated in Figure 4. It includes a CMOS Image Sensor and every electronic function required to operate the sensor, to digitize the pixel signal and to transmit the information to the external optical transceiver, i.e.:

- a High Definition (HD) pixel array made of 1280×720 pixels with a Bayer Color Filter array (one RGB filter per pixel)
- a 10-bit column parallel Analog-to-Digital Converters (ADC)
- an on-chip sequencer
- an on-chip digital communication interface

Each of these integrated electronic functions is radiation hardened using well known radiation-hardening-by-

design (RHBD) techniques [4], [5], especially at the device layout level. The pixel design itself has been treated with particular attention as discussed in [6] to meet the CAMRAD project requirements.

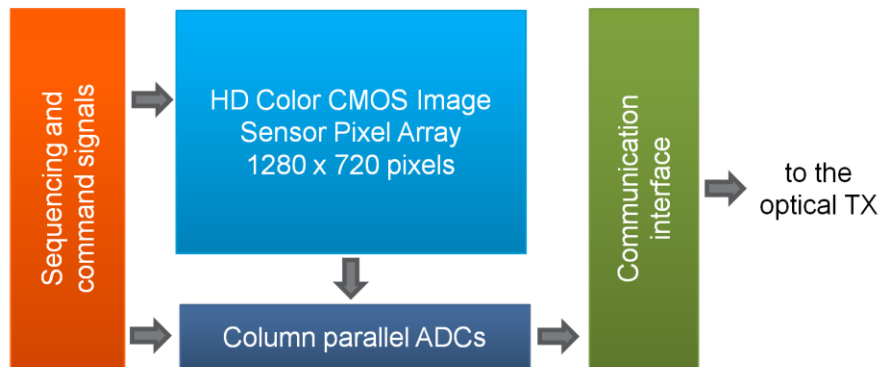


Figure 4 : Illustration of the camera-on-a-chip content.

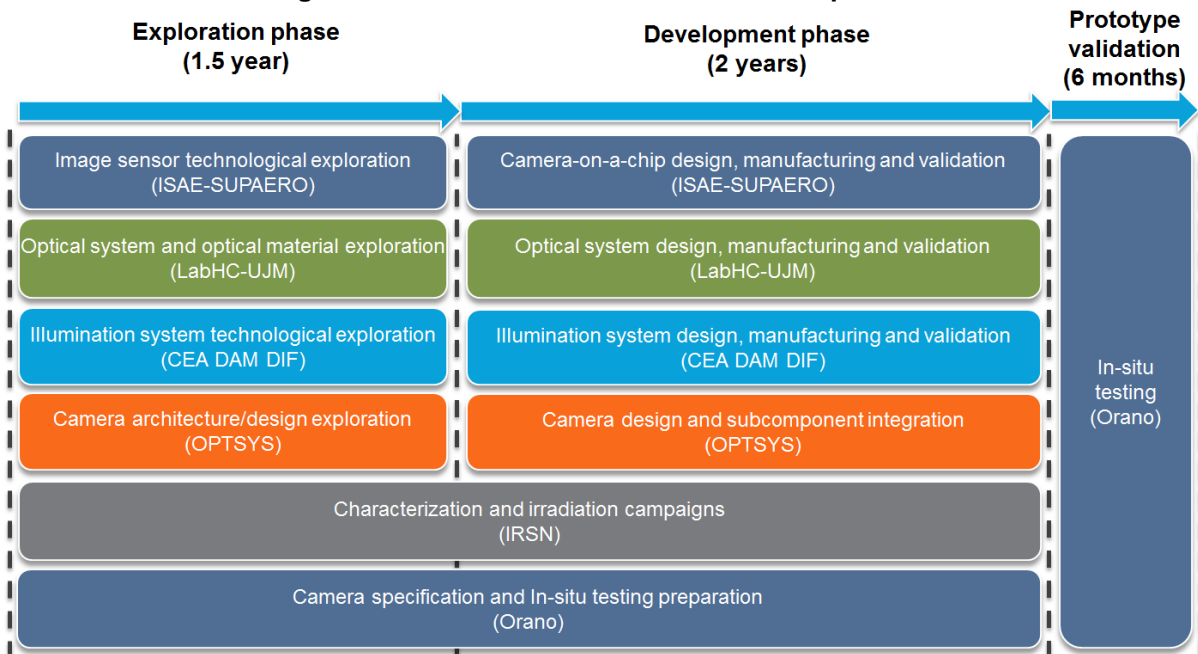


Figure 5 : CAMRAD project organization overview.

The other innovation of the presented project is the development of Multi-MGy optical and illumination systems as well as the parallel optimization of these three key functions in order to reach the project ambition by compensating each subsystem potential weakness by designing accordingly the other two. Such strategy explains that the Light Emitting Diode (LED) technology as well as the optical system materials have been carefully chosen to ensure the best optical budget for this image sensor technology. The nominal CMOS image sensor integration time, the LED optical power and the optical system aperture have been optimized to account for the expected radiation induced degradations or modifications of these subsystems. The exploration phase discussed hereafter is used to extrapolate the behavior of the full-size system after irradiation and to anticipate its limited radiation induced changes.

Finally, the ambition of the developed approach is also original: CAMRAD is seeking to develop a camera with a much greater resistance to ionizing radiation than existing products (cumulative dose of 1-10 MGy) with performance levels and features not generally found on this market (color image, high resolution, compact design, etc.).

Existing radiation tolerant cameras are based on COTS sub-components that intrinsically limit the radiation hardness and the performance of the whole imaging system. The multi-scale radiation hardening approach starting from the selection of the right materials and manufacturing processes, all the way up to component radiation-hardening-by-design and system level radiation-hardening is illustrated by the project flow chart of Figure 5. Beside the overall project architecture, this figure also depicts the role of each partner and highlights their complementarity.

To reach the goal of CAMRAD, the project has been divided into two main phases: a technological exploration phase (May 2016 – February 2018) and a full-scale prototype development and validation phase (March 2018 - May 2020). During the exploration phase, several radiation hardening strategies have been explored for each subpart of the camera. The outcomes of this first phase are detailed in the following sections.

During the second main phase, each sub-system will be developed, validated and integrated inside the camera prototype. To conclude the project, this camera prototype will be itself validated by an in-situ test that is representative of a real application case. This in-situ test will take place at the IRSN IRMA facility. The camera will record images in front of Co⁶⁰ sources. Because of the size of the irradiation room of IRMA (see Figure 6) the scene will be placed at a distance of 1.5 m from the camera. This test has two main goals:

- to demonstrate that the assembled camera can operate and keep the image quality during the irradiation up to 1 MGy
- to study online radiation effects on each subsystem

This in-situ test will enable the study of online radiation effects on a CIS to such a high TID (speckles, dark current...). As the CIS, the LEDs were also tested post-mortem during the exploration phase and this online analysis will probably give us more insights to understand the degradation mechanisms. Lastly, for the optical system we will not be able to discriminate the response of each lens individually, so the degradation of the whole optical system will be assessed. The custom contrast target presented in Figure 7 will be used to evaluate the defocus (induced blur) and objects will be placed on each side of the field of view (1 m away from the scene center) to highlight any image distortion.

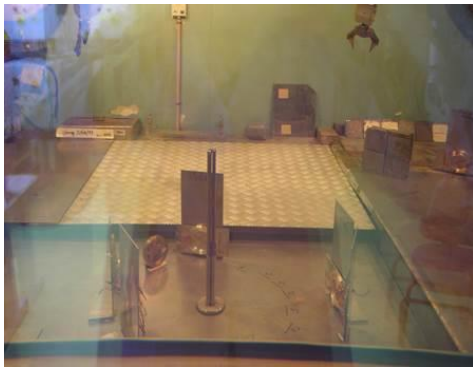


Figure 6: IRMA irradiation room

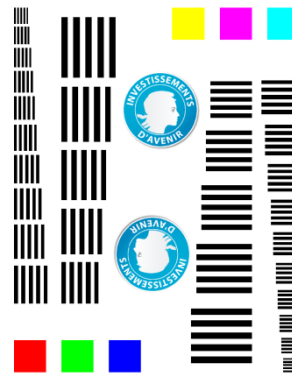


Figure 7: CAMRAD contrast target, the smallest line is 1mm

Exploration Phase Overview

The aim of the exploration phase is to highlight the main radiation induced degradations and to select the best materials, the best technologies or the best designs for each sub-system to ensure at the same time a radiation hardness of several MGy and high imaging performances. An overview of the exploration phase outcomes is given in the following sections for each sub-system.

The common core of the exploration phase is its irradiation test campaigns. Two campaigns have been performed at IRMA facility of IRSN which uses four radioactive sources of ⁶⁰Co (gamma ray: 1.17 and 1.33 MeV) and provides a wide range of dose rates. Various materials and components have been exposed to TID, from a few kGy to 1 MGy as summarized in Table 1. The position of each sample relative to the source support was defined considering the expected dose and the dose rate depending on the source-sample distance (value estimated with simulation and confirmed by dose rate measurements thanks to an ionization chamber).

Table 1 : CAMRAD exploration phase radiation test campaign summary.

	First campaign	Second campaign
Date	2017, October 13 to 27 (14 days)	2017, December 7 to 21 (14 days)
Irradiated samples	Glass samples, LEDs, optical fibers, optical transceivers and other components of interest for the camera.	Glass samples, lenses, LEDs, CMOS image sensors, a zoom, optical fibers and other components of interest for the camera.
Global activity	1010 TBq (2017, October 13)	990 TBq (2017, December 07)
Doses	From 15 kGy(SiO ₂) to 1 MGy(SiO ₂)	990 TBq (2017, December 07)
Dose rate	From 45 Gy/h to 3 kGy/h	From 3 Gy/h to 3 kGy/h
Temperature	Room temperature	Room temperature

Exploration Phase Main Results

Camera-on-a-chip exploration phase outcomes

As mentioned previously, in order to control the radiation hardness of the whole camera electronics, all the required electronic functions (ranging from the image sensor to the communication electronics and on-chip sequencing) will be embedded on a single “camera-on-a-chip” integrated circuit. Previous work has demonstrated that developing a multi-MGy radiation-hard camera on a chip is feasible [3]. To reach the highest performance for the CAMRAD prototype, the radiation hardness of several CMOS manufacturing processes has been explored. Despite some evidences in the literature that deep submicron standard CMOS processes can be used to develop MGy radiation hard pixel arrays [7], CMOS Image Sensor manufacturing processes (i.e. CMOS processes optimized for imaging applications) have been targeted for this project for the following reasons:

- some imaging features required for the project are only available on CIS processes (e.g. color filter arrays);
- and doping profiles, oxide interfaces and dielectric stacks are optimized in CIS technologies to maximize the imaging performances (e.g. low dark current, high sensitivity).

After reviewing all the possibilities, two 180 nm CIS processes (from two different foundries) have been selected. Indeed, this CIS technology node represents today a good tradeoff between cost, performance and availability. A variety of test structures, including Metal Oxide Semiconductor Field Effect Transistors (MOSFETs) and image sensor pixel arrays have been designed and manufactured with the two selected manufacturing processes. These test structures enabled the evaluation of these manufacturing processes intrinsic radiation hardness but also of the efficiency of several radiation hardening by design techniques [4], [5]. Figure 8 presents the evolution of some of the studied RHBD MOSFET threshold voltages with absorbed ionizing dose for the two selected CIS processes. These results are also compared to those obtained on a third CIS processes (from [8]). This graph agrees with the fact that, at this TID level, P channel transistors are always much more degraded than their N-channel counterparts, as reported in [9]–[11] and that low voltage transistors (i.e. 1.8 V MOSFETs) are also much more resistant to TID than high voltage (i.e. 3.3V) ones. More importantly, this figure demonstrates the large influence of the manufacturing process on the radiation hardness with discrepancies that can reach a factor of three between foundries B and C.

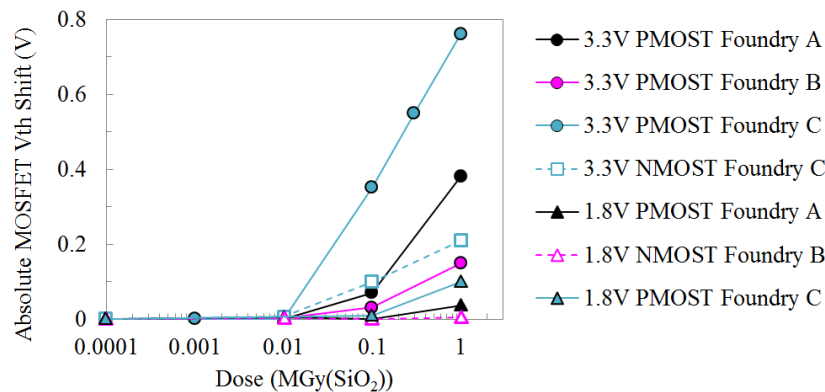


Figure 8 : Evolution of the absolute threshold voltage with TID of the studied radiation-hardened-by-design MOSFETs on the two selected technologies (A and B). These results are also compared to a third technology (CIS process C) from [8]. Nominal biases were applied to these transistors during irradiation. NMOST = N-channel MOSFET. PMOST = P-channel MOSFET.

Pixel array test structures from the two selected manufacturing processes have also been characterized before and after irradiation. Figure 9 shows an image captured before and after irradiation with the pixel array manufactured with the CIS process selected for the next phase of the project. The image is divided into 16 pixel sub-arrays, each with a different pixel design (most of them are radiation hardened designs). It can be seen that after irradiation some pixel designs are not functioning properly anymore (bottom left and top right regions). This image demonstrates that the imaging capability is maintained after the deposition of 1 MGy of TID on most of the explored RHBD pixels. Furthermore, the image quality and the color rendering capability are not significantly degraded in these rad-hard pixel regions highlighting that several solutions exist to reach the goal of CAMRAD. Thanks to the full set of results (detailed in [6]) acquired during the exploration phase, it is possible to select the most suitable technology for the development phase. The performance parameters extracted from the characterization of the studied pixel arrays are also used in the development phase to design the other subsystems of the camera head.

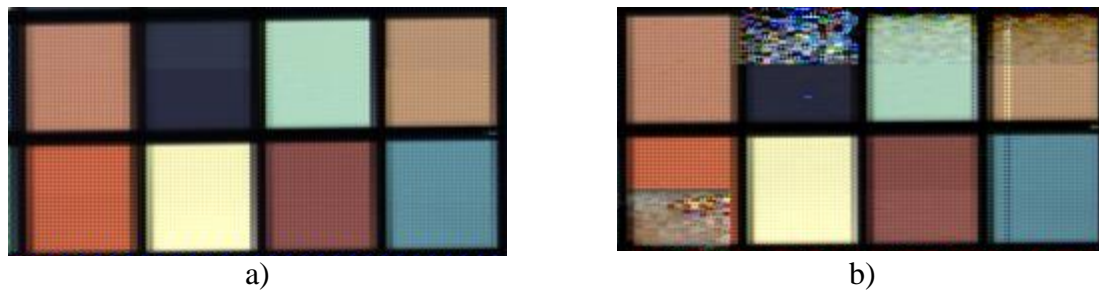


Figure 9 : Raw color image captured by a 128x256 pixel array test structure a) before and b) after 1 MGy(SiO₂) irradiation. The tested pixel array is divided into 16 smaller arrays with different pixel layouts. Radiation hard pixel designs are the ones exhibit no significant image degradations after exposure to ionizing radiation.

Optical system exploration phase outcomes

The main concern about the optical system is the darkening (or RIA for radiation induced attenuation) of its optical lenses [12]. During irradiation electrons and holes are released by ionization [13] and can be trapped by point defects causing the appearance of new absorption bands [1]. This darkening can lead to an absorption of several dB/mm in the visible spectrum [14] [15] and its amplitude and kinetics depend on a number of parameters such as the glass composition. Designed with COTS glasses, optical systems made with mm-thick lenses present after some kGy a darkening level that can prevent the camera to acquire exploitable images.

To prevent the darkening, the optical system will be designed with Radiation Hardened (RH) silica-based glasses that are usually doped with cerium oxide. The two oxidation states of cerium, Ce³⁺ and Ce⁴⁺, can trap electrons or holes helping to prevent the creation of some of the absorption bands causing the darkening [16] [17] [18]. This technique was developed in the 60s and these glasses have permanent RIA lower than 0.5 dB/mm in the visible spectrum after 1 MGy [19] [20]. Hence, by minimizing the number of lenses and choosing a suitable illumination system, we can maintain a sufficient light level on the CMOS image sensor.

To consider the contribution of both transient and metastable defects, online measurements under X-rays have been used to estimate the RIA levels associated to our optical system architecture [21]. By considering dose rates exceeding those expected for applications, a worst case scenario can be established as the lower the dose rate is, the lower the RIA is [22] [18]. Figure 10 presents the transmission of our optical system before and after irradiation. The initial transmission is close to 60% between 500 nm and 800 nm, losses being mainly due to the Fresnel reflections on the lenses surfaces and to the transmission drop below 500 nm caused by the cerium doping. Figure 11 presents the RIA of the selected optical system architecture. The RIA above 450 nm remains below 0.2 dB, the most impacted domain concerns the blue tail of the LED spectrum associated with the illumination system.

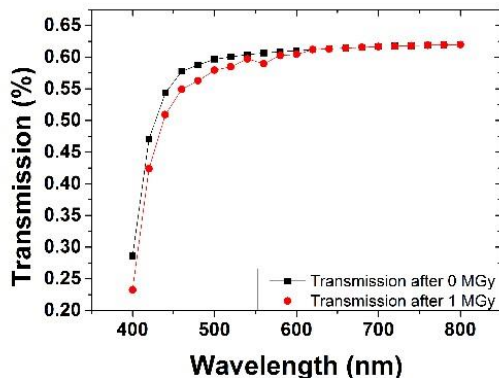


Figure 10 : Transmission of the optical system at 0 and 1 MGy. Data are based on online measurements at room temperature and 45 Gy(SiO₂/s) under X-rays.

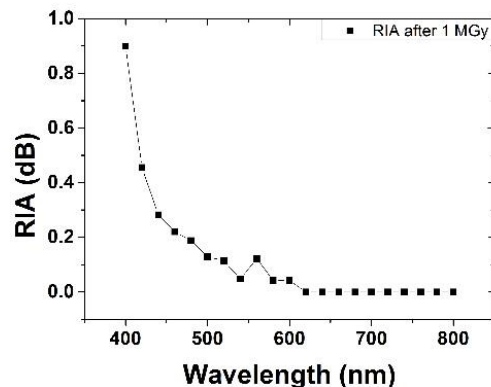


Figure 11 : RIA of the optical system at 1MGy. Data are based on online measurements at room temperature and 45 Gy(SiO₂)/s under X-rays.

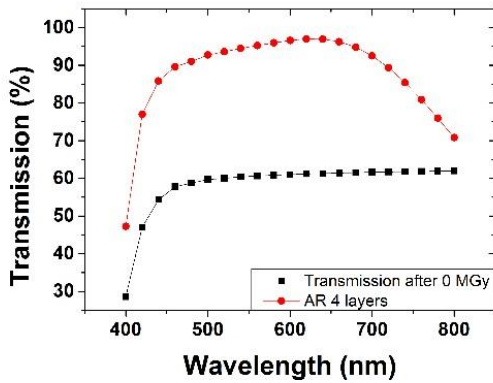


Figure 12 : Effect of a 4 layers AR coating on the optical system transmission.

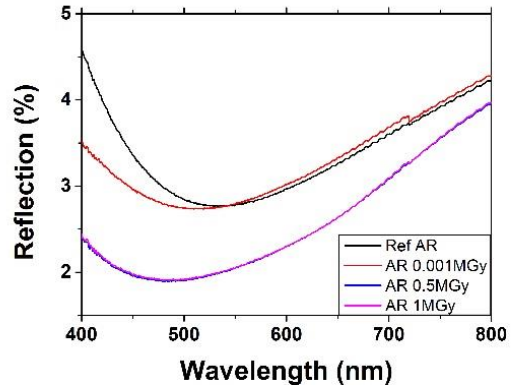


Figure 13 : AR coating measured in reflection at 6° at different irradiation steps.

One solution to increase the system transmission is to use Anti-Reflection (AR) coating. These coatings are based on multi-layer material designed to decrease reflections at the lens interfaces. Figure 12 illustrates the positive effect of applying an AR coating on our optical system transmission. We tested different coating technologies under radiations and a typical result is presented in Figure 13. The radiation effects seem negligible or even positive: the reflection decreases with the dose.

The second worst effect of radiations on glass is the refractive index (RI) change caused by the absorption change or the density change, respectively described by the Kramers-Kronig [23] and the Lorenz-Lorentz relations [24] [25]. This effect has been less studied than the darkening but literature data [19] [26] [27] provide evidence for RI changes up to 10^{-3} .

Our optical system architecture consists in an F/6, 17°-hfov system with a focal length of 20.4 mm. The working distance is 1500 mm and the observed scene is 800×450 mm. It is close to the diffraction limit (Figure 14) in terms of modulation transfer function (MTF) over the whole field. This means that its impulse response – the Point Spread Function (PSF) – is slightly bigger than the diffraction pattern of a circular aperture, known as Airy disk. The MTF is the modulus of the Fourier transform of the PSF, meaning that the smaller the PSF is, the wider the MTF is. The latter can be seen also as the contrast of a sinusoidal signal for a given spatial frequency (in cycles/mm). Since the pixel pitch is $p = 8.5 \mu\text{m}$, the Shannon-Nyquist sampling theorem indicates that the highest recordable spatial frequency is $\nu_{Ny} = \frac{1}{2p}$ which is close to 60 cycles/mm here. Higher frequencies will undergo aliasing.

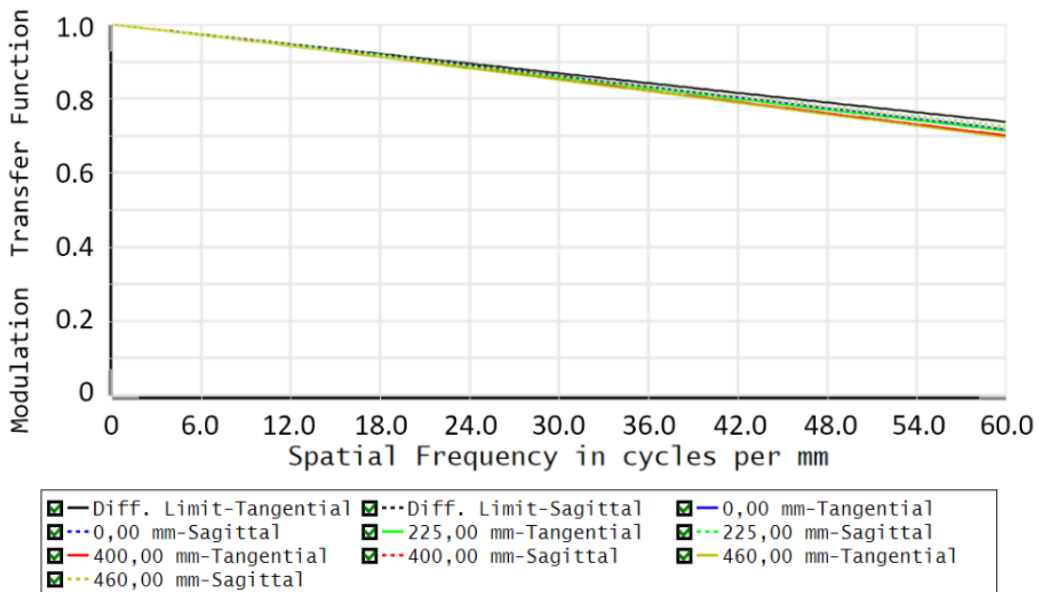


Figure 14 : MTF of the optical system on the optical axis and for different positions in the field: half height (225 mm), half width (400 mm) and half diagonal (460 mm).

In the optical system, the RI change can induce defocusing of the image: the observed scene is blurred. This effect corresponds to an increase of the Point Spread Function diameter and thus to a MTF decrease. Figure 15 shows the MTF at 30 cycles/mm and 60 cycles/mm for a change of refractive indexes up to 10^{-3} for the two different radiation hardened (RH) glasses used to design it. Its performances are maintained for RI changes (Δn) lower than a few 10^{-4} at 60 cycles/mm. The two glasses RI changes do not have the same impact on the performances, the more impacting being the one labeled (RH2). However, if both RI changes have the same sign, their effect can partially compensate which permits to reach higher RI changes with limited performance losses.

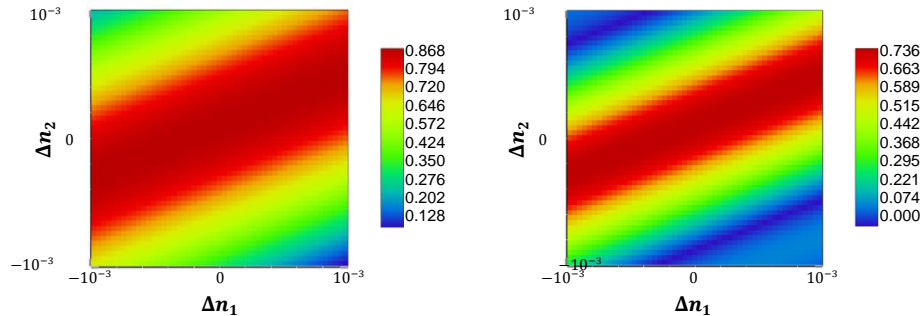


Figure 15 : MTF at $\nu_{Ny}/2$ (left) and ν_{Ny} (right) as a function of the RI change (Δn) of two radiation hardened glasses (RH1 and RH2).

Illumination system exploration phase outcomes:

The illumination system is based on LEDs that are known to combine several interesting advantages : a documented radiation resistance to ionizing radiation [28], a small footprint and an efficient light power emission. Even though LEDs exhibit a high tolerance to TID, other radiations can create non-radiative centers and decrease the output light power [29].

We tested 10 white, 1 Red Green Blue (RGB) and one 1 Red Green Blue White (RGBW) LED references. An integrating sphere and a photospectrometer were used to perform spectral measurements. In Figure 16 we present two typical results, one for a white LED and one for a RGBW LED.

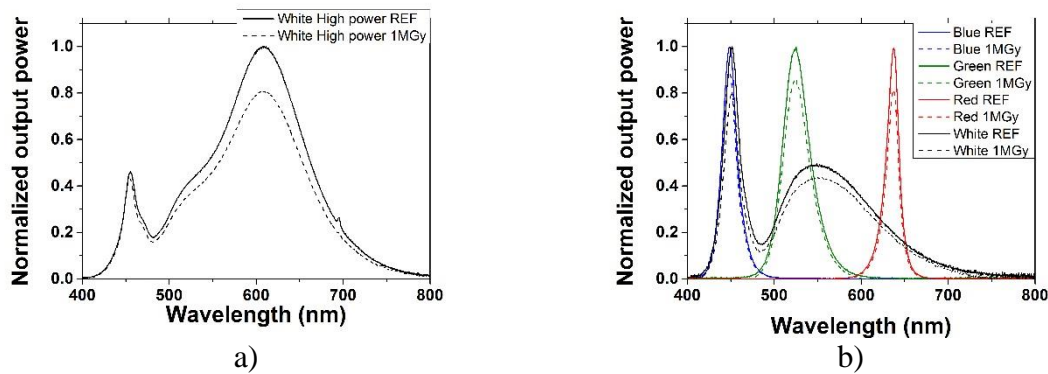


Figure 16 : Emission spectra of a) White High Power, b) RGBW LEDs before and after γ -rays irradiation at a TID of 1MGy.

Both LEDs output powers decrease with irradiation dose; degradation levels are reported in Table 2. The final choice between the different technologies will depend on the results of the photometric calculation. A trade-off has to be made between the camera design, the image quality and the amount of light needed on the scene. The current trend leads toward a combination between High power white and RGBW LEDs. The ability of this option to maintain sufficient power in every spectral channel will be assessed, as well as to adapt the amount of light power in each channel during irradiation. Temperature management also has to be taken into account, due to two opposite effects: higher temperature can act activate annealing of defects, but it is also well known that temperature decreases the output light power. For the CAMRAD project, TID-induced defects should be limited, therefore temperature management is needed to prevent the decrease of output light power.

Table 2 : Output power variation of LEDs presented in Figure 16

RGBW	Power change after 1MGy (%)
Blue	-13
Green	-16
Red	-20
White	-6
	Power change after 1MGy (%)
White High Power	-13

Conclusion and On-Going Work

This paper presents the CAMRAD project and the key outcomes of its exploration phase. These results already demonstrate that solutions exist to build a multi MGy radiation hard color imaging system for dismantling operations. This first comprehensive study of the TID effects on each camera sub-system enables the selection of the most efficient technologies to achieve the targeted imaging performances. This work also allows extrapolating some first specifications for the final imaging system prototype as illustrated in Table 3.

The next phase of the project will consist in exploiting the conclusions presented here to design each sub-system while assuring the targeted level of radiation hardness and performance. In 2019, these sub-systems will be integrated into the camera prototype that shall be validated by the in-situ test. In the end, the developed radiation hard imaging system and its building blocks could benefit to a wide range of applications where it is necessary to observe in a harsh radiation environment, such as nuclear power plant inspection and monitoring or such as space exploration.

Table 3 : CAMRAD camera prototype targeted/expected performance (valid after exposure to the highest TID level).

Parameter/Feature	Targeted/expected value
Format	1280×720 pixels
Frame rate	25 fps
Dynamic range	> 60 dB
Dark current (22°C)	< 0.5 pA
ADC resolution	10 bit
Color	RBG bayer pattern color filter array
Failure TID	> several MGy(SiO ₂), to be determined during the final validation phase

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