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IRRADIATION TESTS OF A DIGITAL RADIATION-TOLERANT CAMERA FOR CERN'S PARTICLE ACCELERATOR INSTRUMENTATION

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Abstract

Beam imaging systems are integral parts of beam instrumentation at CERN, measuring the shape, size, and position of particle beams in accelerators. Following the worldwide phasing out of analogue cameras and vidicon tubes (which the system was initially based on and still partially uses), part of the ongoing consolidation program involves developing a new camera system based on digital technology for use in CERN's medium radiation environments up to few 100 Gy total dose.

For this purpose, the CERN Beam Instrumentation group initiated the development of a digital camera system in collaboration with MCSE, a Swiss company specializing in space instrumentation. The new camera's performance under radiation was evaluated at CERN's CHARM test facility, with promising results in terms of radiation immunity while maintaining sufficient sensitivity and resolution—which will be the focus of this contribution. Following this prototyping phase, an industrial version is now in development and is expected to undergo testing in 2025.

INTRODUCTION

The CERN Beam Instrumentation group (SY-BI) uses cameras in over 200 beam imaging systems to monitor beam presence, position, size, and occasionally for remote equipment inspection. Most systems use interceptive screens emitting light via scintillation or Optical Transition Radiation (OTR), captured by cameras through optical setups [1]. These instruments cover CERN's accelerator complex, including ISOLDE, HIRADMAT, AWAKE, and CLEAR. Historically based on analog cameras, they are now transitioning to digital models due to the phase-out of analog devices. Figure 1 illustrates the principle of such a system as deployed across the accelerator chain.

The consolidation program first focused on identifying reliable digital camera suppliers and evaluating the intrinsic radiation tolerance of their products. Dedicated tests [2] established safe operational limits for commercial off-the-shelf (COTS) cameras, beyond which radiation-hardened solutions are needed.

To address varying radiation environments, programs were launched for both radiation-tolerant cameras—withstanding a few hundred gray (Gy)—and radiation-hardened cameras, designed for several megagray (MGy). A key challenge is not only reaching these dose thresholds but also ensuring resilience against single event effects (SEEs), which can disrupt electronics. Unlike analog systems, where damage appears as degraded image quality, digital cameras are especially vulnerable to SEEs, particularly single event upsets (SEUs), which cause temporary bit-flips in memory or logic, often leading to loss of communication.

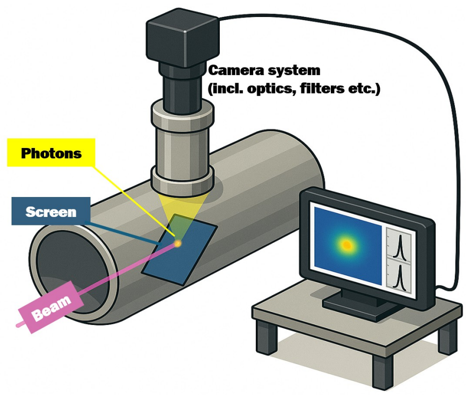

Figure 1: Principle of a camera and screen based instrumentation for beam observation/measurement.

In this paper, we report on the irradiation tests and results for the radiation-tolerant camera "BeamCam", carried out at CERN's CHARM facility [3]. This camera is the result of a collaborative development between MCSE [4] and CERN.

RADIATION TOLERANT CAMERA DESIGN: 'BEAMCAM'

The design is based on an existing MCSE camera originally developed for space applications. It has been adapted for CERN by removing components unnecessary for operation in particle accelerators—such as specialized (and costly) cosmic ray shielding and systems built to withstand extreme conditions (e.g., wide temperature ranges, strong vibrations, and magnetic fields).

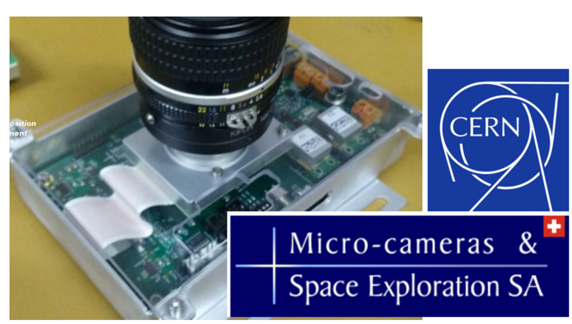

Figure 2: Picture of the 'BeamCam' camera prototype ready for the irradiation test.

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In addition, the design primarily uses qualified commercial off-the-shelf (COTS) components instead of (very expensive or unavailable) radiation-hardened parts. While this limits performance to the 'radiation-tolerant' range, combining the two strategies yields a substantial reduction in the overall system cost. A recent prototype unit, already assembled as imaging sensor and associated electronics equipped with a camera objective, is shown in Fig. 2, The new BeamCam design combines the baseline specifications of the existing system with additional features tailored to the accelerator environment and CERN infrastructure, as summarized in Table 1.

Table 1: BeamCam Specifications and CERN-Specific Requirements

General specifications	
Sensor type	APS, 4 Mpixels (monochrome)
Resolution	10 bit/pixel
Operation	Snapshot and video up to 10 fps
Consumption	< 2.0 W
CERN-specific requirements	
Power supply	Radiation-tolerant DC/DC converter (bPOL12V V6) [5], compatible with +12V input
Optical interface	C-Mount
Synchronization	External triggering capability for beam synchronization
Communication	Gigabit Ethernet (GbE) protocol

The first tests were conducted to assess the system's tolerance to the total ionizing dose (TID). Imaging sensors, with and without selected sets of electronics, were irradiated at CERN—both in mixed-field conditions at CHARM and under gamma irradiation at CC60 [6]—and at the ALTER/RADLAB facility in Spain [7], where gamma irradiation was performed.

The camera assemblies were evaluated after irradiation. They remained operational up to a TID of 36 kRad, although a degradation in image contrast was observed—more pronounced in the mixed-field environment, likely due to displacement damage effects absent under pure gamma irradiation.

The rest of this paper focuses on tests performed at the CERN CHARM facility on the latest BeamCam prototypes. Unlike earlier campaigns, which concentrated on post-irradiation evaluation, these tests aimed to characterize the operability of the camera systems directly during irradiation, under realistic beam-measurement conditions. In particular, the setup allowed us to assess both the potential degradation of image quality and the occurrence of single-event upsets (SEUs), which inherently limit system operability.

IRRADIATION SETUP

The CHARM facility, located in CERN's East Area, receives Proton Synchrotron (PS) spills of up to 5×10^{11} protons, 400 ms long, at 24 GeV/c. The beam strikes a metallic target, producing a mixed radiation field—neutrons, protons, photons, electrons, and muons—via spallation. Resulting dose rates range from 10 μGy/h to 1 Gy/h, with fluxes up to 1×10^9 particles/cm²/s, enabling electronics testing in radiation conditions representative of accelerators, space, and nuclear facilities.

The installed setup is shown in Fig. 3. Two camera prototypes were installed and the irradiation request was for a Total Ionizing Dose (TID) above 400 Gy with a total fluence above 1×10^{12} HeH/cm2. A radiation monitor was placed in the center of the irradiation zone to precisely measure radiation levels and confirm the delivery of the requested dose.

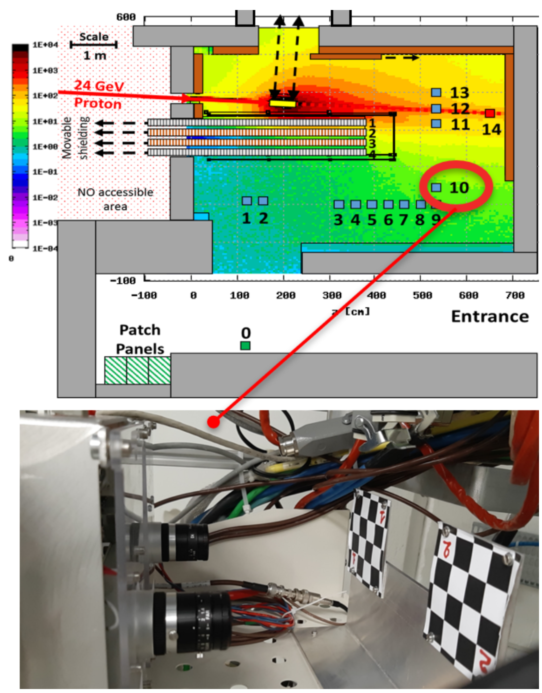

Figure 3: Top: CHARM facility irradiation layout, with the BeamCam setup in location '10'. Bottom: Two BeamCam systems, each with a dedicated black-and-white target to probe visibility.

Test Procedure and Analysis Communication with the cameras was verified before every beam extraction event. Any non-responsive units were reset with a power cycle. Then multiple images were acquired during and after beam extraction, on both running units.

A cumulative counter of SEE was setup for each digital camera, used to track Communication failures and Acquired images showing clear pattern anomalies such as mirroring, pixel intensity spikes, or swapped rows/columns artifacts.[1]

[1] Some of these effects may also stem from non-optimized FPGA firmware, which will be upgraded in the final version. Attributing all cases to SEE is thus a conservative assumption.

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RESULTS

For each camera, overall reliability was evaluated by combining the cumulated SEE—inferred from the number of power cycles— with the measured fluence. The evolution of image contrast during irradiation was used as a second key performance indicator. In addition, the camera supply current was monitored to assess irradiation effects at the electronics level.

Sensitivity to Single Event

From irradiation data summarized in Table 2 it is possible to estimate a cross section σ_{SEE}—the probability that a particle interacting with the camera will produce a SEE—and the fluence for failure $\Theta_{failure}$ as:

$$\sigma_{SEE} = 1/\Theta_{failure} = N/\Theta_{HeH} \tag{1}$$

where N is the number of observed SEEs and Θ_{HeH} the total high-energy hadron equivalent fluence.

Table 2: Irradiation Data Summary (in Bold the Parameters Relevant to Assess the Sensitivity to SEE)

Parameter		**Value**
Proton on Target	POT	8.5×10^{16}
Total Ionizing Dose	TID	**430.1 Gy**
High-energy Hadron fluence, $E > 20$ MeV	Θ_{HeH}	$\mathbf{1.01 \times 10^{12}\ cm^{-2}}$
Thermal neutron fluence, $E < 0.4$ eV	ThN	1.00×10^{12} cm^{-2}
1 MeV neutron equiv. fluence	N1MeV	5.76×10^{12} cm^{-2}

Table 3 summarizes the cross sections and fluence for failure of both BeamCams, along with the camera supply current increase measured over the 5-weeks irradiation period.

Table 3: Power Cycles, Dose, and SEE Cross-Section for BeamCam1 and BeamCam2

	BeamCam1	**BeamCam2**
Power cycles	41	50
σ_{SEE} [cm^2]	4.06×10^{-11}	4.95×10^{-11}
$\Theta_{\mathrm{failure}}$ [cm^{-2}]	2.46×10^{10}	2.01×10^{10}
Current increase [%]	4.6	3.6

Visibility Evolution

The visibility V of an imaging system can be quantified through the contrast ratio (CR), defined as the relative difference between the maximum and minimum image intensities:

$$\vee = (I_{max} - I_{min}) \,/\, (I_{max} + I_{min}) \tag{2}$$

with I_{max} and I_{min} the image brightest and darkest points respectively.

By definition: $0 <= \vee <= 1$. The two cameras' visibility evolution during the irradiation period is shown in Fig. 4. along with the cumulated TID. Only BeamCam2 displays reduced visibility in the 50 Gy to 200 Gy range. This early degradation is likely attributable to its previous gamma irradiation at ALTER/RADLAB, whereas BeamCam1 was newly deployed for these tests.

Both systems experienced a visibility drop of 50 % to 80 % after approximately 200 Gy. Between 200 Gy and 250 Gy, visibility stabilizes at approximately 20 %, which we adopt as the reference threshold below which the signal-to-noise ratio of the beam measurements become unacceptable.

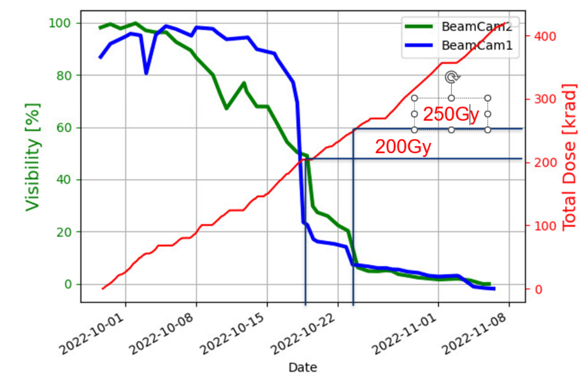

Figure 4: Visibility evolution, as continuously monitored during the irradiation test.

SUMMARY

Two BeamCam digital camera prototypes, developed by MCSE and CERN, were irradiated for 5 weeks at the CHARM facility, reaching a TID of 430 Gy and a fluence of 1.01×10^{12} cm^{-2}. Their measured SEE cross section was at least 15 times lower than that of COTS cameras under similar conditions [2], qualifying them as radiation-tolerant. Some SEEs are likely due to FPGA issues rather than sensor failures, suggesting further resilience gains.

A modest supply current increase was observed after 430 Gy, confirming component robustness. However, image contrast degraded beyond 200 Gy to 250 Gy, with visibility dropping to 20 %, marking a practical upper limit for beam monitoring.

These results demonstrate BeamCam's suitability for medium-radiation environments at CERN, offering a cost-effective, scalable replacement for analog systems. Further industrialization and testing are foreseen to enhance reliability and broaden capabilities.

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