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UPGRADE AND EVOLUTION OF THE AD TARGET BEAM IMAGING SYSTEM AT CERN: A TWO-YEAR PERFORMANCE ANALYSIS

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Abstract

During CERN's Long Shutdown 2 (LS2) in 2021, the Anti-Proton Decelerator (AD) target area underwent major renovations, including a significant upgrade to its beam imaging system. The previous tube-based camera, used in a high-radiation environment, had limitations in sensitivity and resolution for continuous measurements. The upgraded design uses an innovative in-air light-emitting screen mechanically coupled to the AD target, monitored by a digital camera through a 20-meter optical line from a radiation-safe zone. This setup improves accessibility during beam operation and enhances measurement capabilities. Over two years of operation, several crucial modifications were made. A key change was transitioning from a scintillation material screen to an Optical Transition Radiation (OTR) screen, though this created new challenges with background interference. To address temperature-dependent calibration variations, an automated calibration mechanism was developed, utilizing advanced image analysis algorithms for real-time adjustments.

INTRODUCTION

The AD target area required major consolidation [1,2] due to aging and obsolete equipment—including the target, magnetic horn, and support infrastructure—in order to mitigate significant safety risks and ensure long-term operational reliability beyond 2030. The upgrade also aimed to improve the reliability and efficiency of antiproton production. As part of this effort, new instrumentation was requested to measure the beam size and position in front of the AD target for all extracted beams, with a resolution better than 250 µm. This capability enables online verification of the target setup's integrity and helps ensure optimal antiproton yield for physics experiments. Table 1 lists the beam parameters delivered to the new AD target station from the Proton Synchrotron (PS).

Table 1: Nominal Parameters of the Beam Delivered to the AD Target

Parameter	Value
Type	Protons
Energy	26 GeV
Intensity	1.5×10^{13} ppp
Annual intensity	2.0×10^{18} POT
Length	450 ns
Repetition Rate	0.01 Hz
Size at target	$\sigma_x = \sigma_y = 1$ mm

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A critical factor is the intense radiation generated during antiproton production, which results in significant activation of the surrounding area. To achieve 100 % measurement availability while minimizing maintenance, the system employs a fixed scintillating screen, with the emitted photons relayed over a 20 m optical path to a camera located in a radiation-free area. The optical line (see Fig. 1) consists solely of flat mirrors, with no intermediate focusing elements; all image formation, magnification, and focusing are performed by a large-aperture final camera lens (Fig. 2). This configuration preserves image quality, minimizes aberrations, and maintains the required depth of field over the entire optical path.

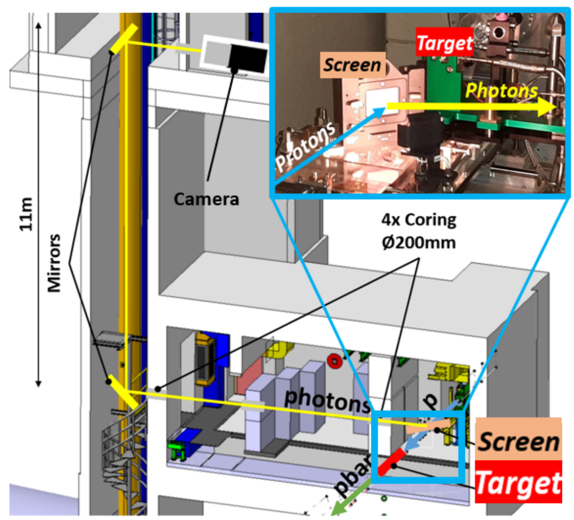

Figure 1: Optical layout of the AD target beam imaging system, highlighting the target/screen station.

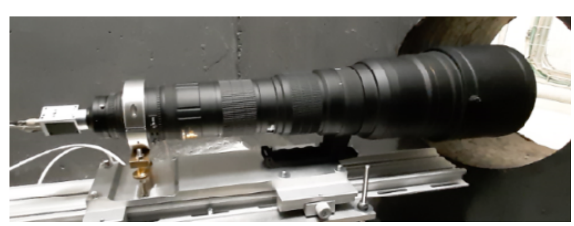

Figure 2: Large-focal-length camera lens with digital camera, installed in a dedicated blackened, radiation-free room.

DESIGN EVOLUTION

The system is based on a screen mounted on a frame designed for quick installation and can be removed via a fast connection system. This design follows the "As Low As

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Reasonably Achievable" (ALARA) principle to minimize exposure in the highly activated area, and features alignment calibration marks on the screen frame that ensure the screen can be replaced without requiring a new survey.

Although the total radiation dose at floor level in the room adjacent to the target remains below 18 Gy per run, simulations of the High Energy Hardron (HeH/cm2) -equivalent fluence indicate values several orders of magnitude higher than the BASLER camera's qualified tolerance at CERN's CHARM facility [3]. Therefore, the camera must be positioned at least 8 meters above floor level to remain within a safe radiation zone.

The optical line, simulated using *Zemax OpticStudio 18.1* [4], consists of two high-quality mirrors measuring 300×200 mm^2 from OptoSigma, featuring a surface accuracy of $\lambda/5$ and a scratch/dig specification of 20/10. These mirrors guide the light to a safe location 20 m away, as required by radiation safety constraints. The optical setup is completed with a camera lens from Sigma set to a 600 mm focal length and an f-number of f/5.6. Simulations and optical tests confirmed that a pixel on target of 110 µm is achieved, with a point spread function (PSF) measured by the pinhole technique of 90 µm. The control and acquisition system is VME-based. Both the digital camera and the illumination system may require case-specific adjustments, which are essential for accurate image calibration.

Chromox Screen Degradation

The imaging system was initially based on a scintillating Chromox (Al_2O_3:CrO_2) screen. The same screen type was used in the previous installation at this location, lasting over two decades in air. In the new installation, however, noticeable degradation appeared after only a few weeks of operation (see Fig. 3).

Although the screen did not break—confirming its robustness against radiation—it became visibly discolored (with a burnt appearance) at the beam impact location. This occurred after an exposure of approximately 6×10^{16} POT (Protons On Target) at a density of 1.5×10^{13} ppp (protons per pulse). Such an exposure has been exceeded in other in-vacuum screens at CERN and did not cause similar damage. The likely cause is the combination of high density and operation in air, leading to oxygenation and surface marking of the screen, thereby compromising precise profile measurements.

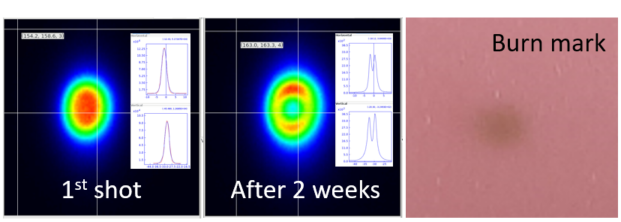

Figure 3: In-air Chromox screen on the AD target instrumentation, showing burn-like degradation after two weeks of nominal beam operation.

Upgrade to GlassyC Screen

Following the observed degradation of Chromox, an alternative material should be selected. For proton beams of this intensity and energy in air, there is no obvious scintillating alternative and it was decided to test SIGRADUR® GlassyC [5] for which photons are emitted via Optical Transition Radiation (OTR) [6]. Two main factors could limit the system's performance with the new screen type: the highly directional nature of backward OTR emission, for which the optical line was not optimized, and the significantly lower OTR proton-to-photon yield -about three orders of magnitude- compared to scintillation.

To address this, before considering the option for intensified cameras, tests were conducted with the existing Basler-Aca2040-35gm digital camera which offers high sensitivity, very good signal-to-noise ratio and a digital gain of up to 200 — unused in the Chromox setup.

Figure 4 shows the installed GlassyC screen and the first beam measurements, confirming that the photon yield and collection are sufficient for beam imaging. On the lower-left corner of the Gaussian beam, the figure also shows evidence of a pronounced 'ghost' image or tail.

Among various hypotheses proposed to explain the origin of this tail:

- **Cherenkov radiation** was excluded, as its production requires charged-particle energies exceeding 38.3 GeV.
- **Air luminescence** was tested by inserting a 250 nm high-pass filter, which blocks photons from the main nitrogen component of air; this confirmed that air luminescence was not the source of the parasitic light.

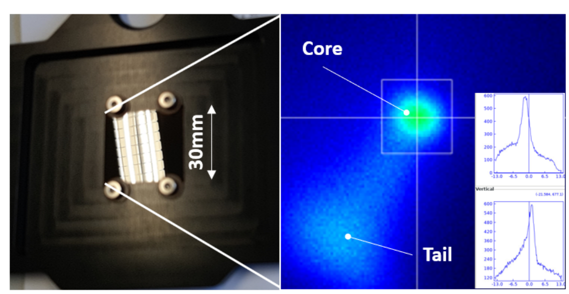

Figure 4: Left: GlassyC screen installed on its support on the AD target instrumentation. Right: first OTR measurement obtained.

Further investigations, revealed that an aluminum cover was installed 1.7 m upstream of the screen on a permanent magnet for safety reason. While, fully transparent for the beam, its interaction generates forward OTR, which is transported along the optical path and likely reflected onto the Glassy C screen (reflectivity 14 %, polished to 50 nm). Simulations are still ongoing to benchmark the measurement.

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Results

The "ghost" image was eliminated by placing a GlassyC blocking foil (BF) in front of the imaging screen. However, the BF itself generates forward OTR, located so close to the imaging screen that the two signals effectively superimpose. Due to the very short separation between the two screens (25 mm), the resulting effect corresponds to approximately a doubling of the collected OTR light intensity) [7]. The layout and effectiveness of the BF in removing the 'ghost' image are shown in Fig. 5.

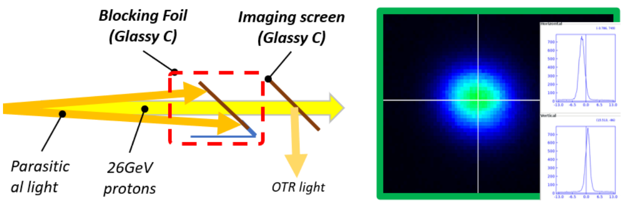

Figure 5: Left: Imaging system layout with the BF in front of the imaging screen. The forward OTR generated on the BF (see text) is not shown. Right: Beam image after installing the BF.

PROTON BEAM AUTO-STEERING

Given the nominal proton beam size (1 mm sigma) and the AD target cross section (3 mm diameter), keeping the beam on-axis is essential to maximize antiproton yield. This is achieved by using beam imaging measurements as feed-forward for beam steering, which requires precise system alignment to correlate photon image position on the camera with the proton beam position on the target.

In spring 2024, a significant spread in antiproton production was observed, clearly correlated with beam position measured on the camera. A periodic displacement suggested ambient temperature effects deforming optical line mirrors or holders. With large lever arms, even small mirror shifts can displace the beam spot on the camera without reflecting real proton motion.

Initially, alignment was done manually with fiducial markers—reliable in most CERN systems but less stable here, as temperature effects required frequent recalibration of image offset. To solve this, a fully automated calibration pipeline using computer vision [8] was developed. Pre-processing (background subtraction, Gaussian blur, intensity normalization) enhances fiducial marker detection. Three methods were implemented: 1/ Curve fitting on intensity projections using Gaussian and Difference-of-Sigmoids (DoS) to extract centroids. 2/ Gaussian mixture models applied to per-row/column fits for robust centers. 3/ SIFT + RANSAC [9] for robustness to lighting and distortions, extracting sub-pixel offsets from matched keypoints. Figure 6 compares methods 2 and 3.

The calibration runs automatically every 20 minutes under CERN's Unified Controls Acquisition and Processing (UCAP) server. Sanity checks and alarms are built-in for

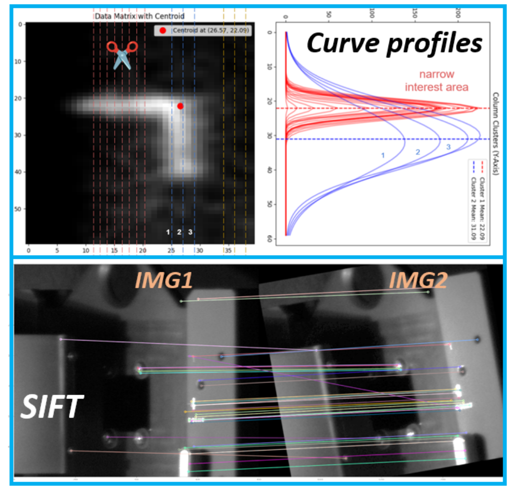

Figure 6: Top: Gaussian curve fitting technique based on profile intensity. Bottom: SIFT + RANSAC approach using targeted keypoint recognition.

fault detection and reliability. This system compensates for drifts, maintaining accurate beam alignment. Future improvements include smarter Region-Of-Interest (ROI) selection and the integration of deep-learning-based keypoint detection. Figure 7 compares antiproton production with and without the auto-calibration feature over 24 hours in summer period. While production is compared across two different years (ideally yield should be compared), it remains evident that daily temperature effects were corrected in 2024 compared to 2023.

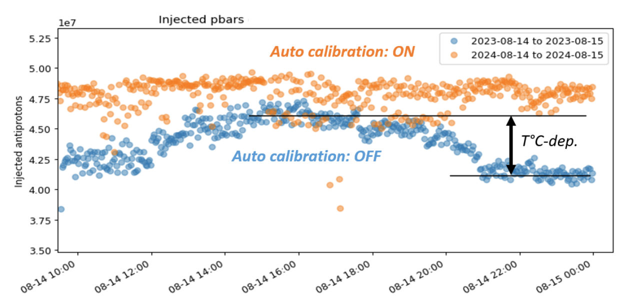

Figure 7: Plots comparing antiproton production with image auto-calibration ON (2024) versus none (pre-2024).

CONCLUSION

The AD target beam imaging system has undergone several upgrades. The first major improvement was the replacement of the Al_2O_3:CrO_2 screen with an OTR Glassy Carbon screen, along with the installation of a nearby upstream blocking foil to remove most of the parasitic light. The observed temperature dependence on the measured position—and its significant impact on antiproton production efficiency, prompted the development of an automatic calibration system based on computer vision. After several months of operation, this solution has proven to be both effective and reliable.

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