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REVIEW OF CERN BEAM INSTRUMENTATION FOR FIXED TARGET EXPERIMENTS

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Abstract

Measuring beam parameters in the vicinity of fixed target experiments or interceptive devices like beam dumps is essential to ensure efficient fixed target physics and safe beam operation. At the same time the beam diagnostic reach is very often challenging in terms of robustness and performance. This paper reviews the CERN instruments exploited to measure protons at different CERN fixed target facilities (ISOLDE, PS East Area, AD, SPS North Area, HIRADMAT) and beam dumps (SPS, LHC), focusing on recent developments/results, limitations and future plans. Emphasis will be given to beam size and beam position monitors systems and their response to high power and/or density proton beams at target locations, including considerations of radiation hardness, backgrounds and power deposition. The discussion will also refer to new materials studies and modern machine learning techniques developed to enhance the overall accuracy and reliability of the monitors.

INTRODUCTION

This paper presents a review of the beam instrumentation for fixed target facilities at CERN (see Table 1) and upstream transfer lines, where radiation and high power beams are often a concern.

Table 1: Overview of CERN Fixed Target Facilities

Energy [GeV]	**Facility**	**Max P** [kW]	**Stored E** [kJ]
1.4	ISOLDE [1]	6.2	7.4
20	nToF [2]	26	32
24	PS EA [3]	16	19
26	AD Target [4]	52	62.4
400	SPS NA	400	1920
440	HIRADMAT [5]	106	2433
450	SPS Dump [6]	180	4100
7000	LHC Dump [7]	n.a.	500e3

BEAM IMAGING DIAGNOSTICS

A small fraction of the over 200 imaging systems using screens at CERN [8] are located near beam dumps and targets. The main challenge here is to design an instrument with a screen capable to withstand high beam power densities and an optical detection system capable to survive high radiation doses. We present three examples of recent developments made at CERN.

SPS Beam Dump System (SBDS) The SPS proton beams not sent to downstream facilities are dumped on to a multilayer absorber, after 'dilution' to minimize power density deposition. The beam footprint is imaged via a Chromox (Al2O3:CrO2) screen installed before the dump [9]. The Chromox saturates depending on the beam intensity, size, and dilution strength, with a decay time of a few hundred milliseconds. Images are captured at 35 Hz and the online software selects the first non-saturated image and publishes it. To reduce the dose on the camera and camera lens, a 17 m long optical line has been designed to move the camera away from the radiation. Novel techniques based on machine learning have been already successfully used to systematically correlate abnormal beam dump images with wrong extraction system settings ormisfiring [10].

AD Target At the Antiproton Decelerator (AD) facility antiprotons are produced by impacting 26 GeV protons onto a fixed target. The beam imaging in front of the target was renovated in 2020 to use a Chromox screen (in air) and a 20 m optical line. However, the screen deteriorated after exposure to only 1e14 protons, probably due to oxidation, so a more durable Optical Transition Radiation (OTR) screen made out of Glassy-C [11] was adopted instead. Despite its lower light yield compared to the Chromox screen, it proved effective after suppressing parasitic light emitted by the beam upstream with a blocking foil installed a few cm in front of the screen. More than 2e18 Protons On Target (POT) were collected in 2022. Figure 1 summarizes the experience with the two screen types.

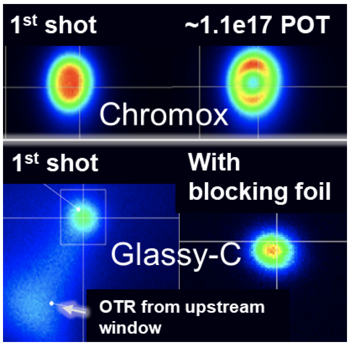

Figure 1: Visual summary of the experience with Chormox and GLassy-C foils for imaging the AD target beam.

HIRADMAT One of the SPS extraction lines hosts HIRADMAT [12], an irradiation facility fed with a maximum of 288 bunches (of LHC beam type, <1 ns long, 25 ns bunch-to-bunch spacing) at 440 GeV, with intensity per bunch that

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can exceed 1.2e11 protons and RMS beam sizes as small as 0.25x0.25 mm. Beam imaging systems are used to check the particle position and density upstream of the targets. The system development included a set of dedicated experiments to characterize different screen materials [13]. Classical materials like Chromox showed fast aging, whereas Glassy Carbon proved to be reliable and resistant. Novel materials tests will be presented in the R&D section of this paper.

SECONDARY EMISSION MONITORS

Secondary Emission Monitors (SEMs) are used at CERN in different layouts and filling factors, ranging from movable thin wires to grids and foils, and with data acquisition systems adapted for the different beams. The latest generation of grids were designed to improve reliability and robustness, even in high radiation zones like those close to targets or dumps. As shown in the example of Fig. 2, instead of traditional wire bundles to be soldered and routed individually, the signals are now read out via flat cables that can be plugged in through connectors. Two types of rad-hard flat cables are used in different locations: one made of 'standard' Kapton and one made of Liquid Crystal Polymer (LCP) material when ultra-high vacuum compatibility and resistance to high temperatures are the most critical requirements.

At the ISOLDE facility [1], SEM grids are essential for steering and characterizing the beam (1.4 GeV protons in bunches for a total of about 3e13 protons) in the transfer line from the Proton Synchrotron Booster (PSB) to the two target stations. Just upstream of the nToF [2] target station, fixed SEM grids are used not only for supporting beam steering and focusing checks, but also as an interlock system to stop the proton beam in case the beam power density is too high to ensure the target integrity. The beam consists of 20 GeV protons in pulses up to 1e13 protons as short as 5ns (RMS) and a repetition rate of 1.2s. This corresponds to about 26 kW average power. In 2022, a total of about 2.5e19 protons were accumulated and the grids, which were installed in 2021, worked reliably. SEMs are also used in the transfer lines to the PS East Area and SPS North Area fixed target facilities. They are used for beam steering and for optics, transmission, and POT measurements. The instruments are stacked a few cm upstream of each of the SPS targets, an example of which is shown in Fig. 3. Absolute intensity measurements are particularly challenging due to the dependence of the secondary emission yield on the material type and radiation/vacuum history. Recent progress on this topic is presented in another contribution [14].

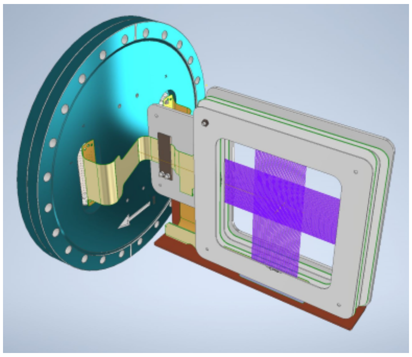

Figure 2: SEM grid model showing the latest design generation with plug-in flex cables instead of soldered bundles.

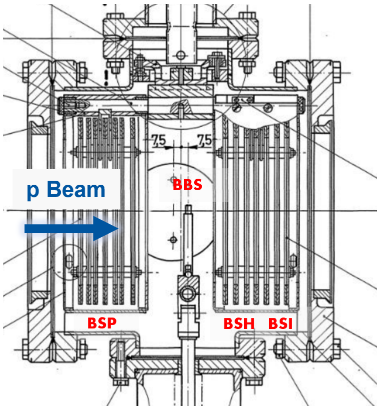

Figure 3: SEM detectors as installed upstream of each SPS NA target. BSI=foil for intensity measurement, BSP=split foil foil for position, BSH=slits for halo, BBS=movable strip for profile.

BCT AND BPM

At HIRADMAT [12], Beam Position Monitors (BPMs) and Beam Current Transformers (BCTs) are used to efficiently transport the proton beam from the SPS to the experimental hall. As shown in Figs. 4 and 5, the system closest to the targets experienced perturbations due to backscattered radiation, which scaled with the density of the target material. The problem with the BCT was mitigated by moving the detector and its front-end electronics some 50 meters upstream. However, for the BPMs (several in the line were perturbed, not only the last one), it is not possible to move the detectors. Moving the front-end electronics to a radiation-safe area did not mitigate the problem, indicating that radiation is affecting the sensors and/or their feedthroughs and cables.

R&D ACTIVITIES

The worldwide production of tubes and CCD cameras, used at CERN in radiation areas, is being discontinued. Alternatives to these technologies are therefore under development by the CERN BI group. A comprehensive set of radiation surveys and simulations has allowed for the definition of 3 radiation environment levels, each requiring different solutions for the camera and detection schemes. *Level 1*: Low radiation in which off the shelf cameras can be used. Irradiation tests at the CERN CHARM facility validated the selected digital camera (Basler, 2017) up to a Total Integrated Dose (TID) of about 100Gy and resulted in a Single Event Effects (SEE) cross-section of $\sim 7 \times 10^{-10}$ cm^2. *Level 2*: Radiation up to 350Gy - radiation-tolerant camera are used, the type of which depends on the beam

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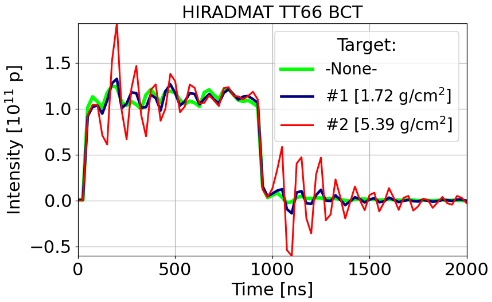

Figure 4: Beam current transformers signals without target and with two high Z targets, before its displacement to a location immune to back-scattered particles.

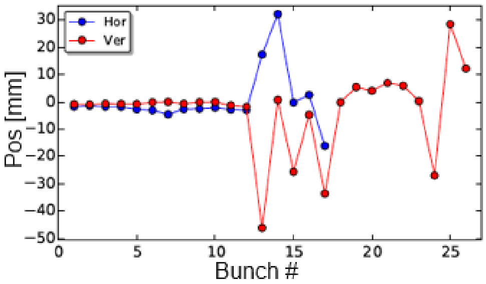

Figure 5: Example of a beam position measurement perturbed by particles bacskacttering from the target. The non-physical position reading of bunches after slot 12 was common on many BPMs sharing the same electronics.

fluence (e.g. analogue CCD, commercial rad hard and tube-based). *Level 3*: Radiation > 350Gy - tube-based cameras and a few radiation-tolerant/hard commercial cameras are used.

In a collaboration between CERN and a private company [15] irradiation tests of a new radiation-tolerant camera model were completed in 2022. As seen in Fig. 6, the system was validated to have good visibility contrast up to a total dose of 250 Gy, with a SEE cross-section of about 4×10^{-11} cm^2. More details can be found in [16]. A version of this camera in an industrial format is in preparation.

For Level 3 radiation zones, there are three noteworthy CERN projects. The first involves an imaging system based on rad-hard fiber bundles optically coupled to a screen and camera sensor. While the principle has been proven through extensive studies and experiments [17], development has been halted due to cross-talk issues and product discontinuity. Another project aims to use AI to reconstruct beam images transported along a single fiber, with promising initial results [18].

A third activity is on the development of a radiation-hard CMOS camera in collaboration with ISAE [19]. A prototype of the camera sensor was tested at CHARM, but the results were inconclusive. Ongoing discussions are being held to test a new model (MegaRAD CMOS) where the communication part still needs to be designed for radiation conditions.

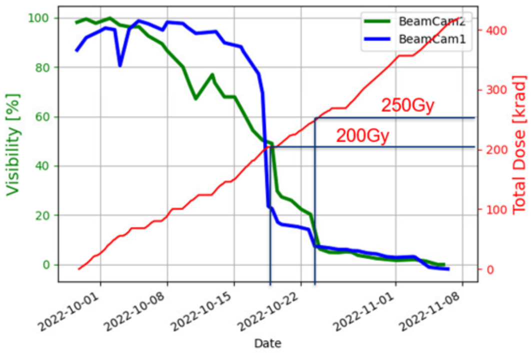

Figure 6: Visibility of prototype rad-tolerant camera as a function of irradiation dose at CHARM.

Research is being conducted on low-density materials that are suitable for beam imaging and can withstand higher beam powers than standard materials. Boron Nitride Nano Tubes (BNNT) scintillators [20] are a promising option due to their good thermo-mechanical stability, UHV compatibility, and a scintillation decay time of few ns. The BNNT producer [21] provided CERN with 2mg/cm2 foils, which were installed at HIRADMAT. Initial measurements comparing BNNT (Fig. 7) to Chromox and Glassy C foils showed that BNNT could image a single bunch and with an accuracy within a few % of the other materials. After normalizing for integration time, camera gain, and optical filters, the light yield of BNNT was found to be 5e-2 of Glassy C and 2.5e-4 of Chromox. However, BNNT foils started to give distorted images with more than 60 bunches, corresponding to a proton density above 1e14 p/cm2, and the BNNT was found to be damaged when removed, with holes where the beam was impacting.

Based on experience with Carbon Nano Tubes (CNT) [22] for wire scanners [23], preliminary tests were performed with foils for imaging. The foils were difficult to mount and stretch on a frame, which resulted in distorted images and broke at a similar power density as the BNNT samples. The BNNT and CNT samples impurities may explain the early breakage.

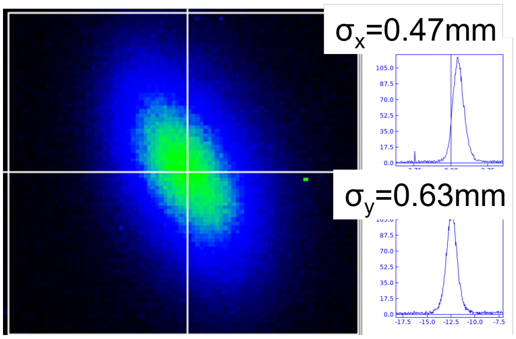

Figure 7: Image of a single bunch (9e10p, 440 GeV) as captured by a BNNT screen, with a camera integration time 2 ms and no optical density filters.

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