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BEAM PROFILE MEASUREMENTS AS PART OF THE SAFE AND EFFICIENT OPERATION OF THE NEW SPS BEAM DUMP SYSTEM

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Abstract

In the framework of the LHC Injectors Upgrade (LIU) project, the Super Proton Synchrotron (SPS) accelerator at CERN is undergoing a profound upgrade including a new high-energy beam dump. The new Target Internal Dump Vertical Graphite (TIDVG#5) is designed to withstand an average dumped beam power as high as 235 kW to cope with the increased intensity and brightness of the LIU beams whose energies in the SPS range from 14 to 450 GeV. Considering such highly demanding specifications, the constant monitoring of the device's status and the characteristics of the beams that are dumped to it is of utmost importance to guarantee an efficient operation with little or no limitations. While the former is ensured with several internal temperature sensors, a Beam Observation system based on a scintillating screen and a digital camera is installed to extract the profile of the beam dumped in TIDVG#5 for post mortem analysis. This paper describes the overall system that uses the BTV images to contribute to the safe and efficient operation of the SPS Beam Dump System (SBDS) and hence the accelerator.

INTRODUCTION

While the accelerators of the proton injector chain at CERN deliver beams to the Large Hadron Collider (LHC) within specification, the requirements for the upgraded High-Luminosity LHC (HL-LHC) exceed their current capabilities. The LHC Injectors Upgrade (LIU) project aims to address this by upgrading the proton injectors to deliver the high brightness beams needed by the HL-LHC [1].

In the framework of the LIU project, the SPS underwent several important upgrades including a new high-energy beam dump [2]. Such a system is meant to dispose of the circulating beam in the accelerator whenever necessary, i.e. in case of emergency, during machine developments (MD), LHC beam setup or LHC filling and after the slow-extraction process to eliminate the remnants of the beam for fixed targets (FT). In order to minimise the associated thermo-mechanical stresses in the dump, the energy density deposited in it is reduced by diluting the beam with the kicker magnets, producing a sinusoidal pattern on the front of the first absorbing dump block [3]. The principle is depicted in Fig. 1 along with a simulation of the expected dilution of a Fixed Target beam.

Until now, the SBDS consisted of two internal dumps, i.e. Target Internal Dump Horizontal (TIDH) and Target Internal Dump Vertical Graphite (TIDVG#4) which used to absorb beams with energy from 14 to 28.9 GeV and between 102.2 and 450 Gev accordingly. During CERN's Long Shutdown

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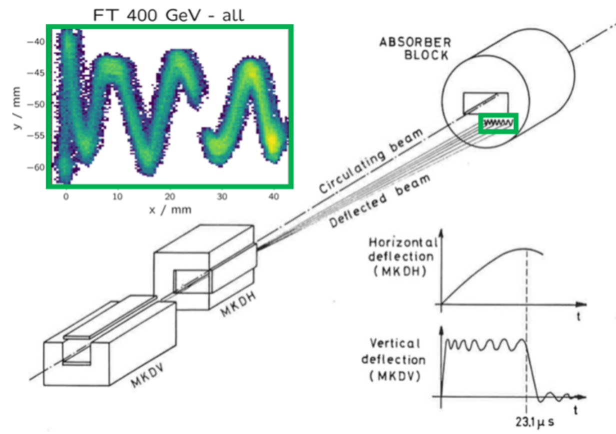

Figure 1: Principle of beam dumping in the SPS and simulation of a Fixed Target diluted beam.

2 (LS2) (2019-2020), the new TIDVG#5 replaced both the aforementioned dumps in order to cope with the increased intensity and brightness of the LIU beams which are expected to produce an average dumped beam power as high as 235 kW instead of 60kW. Consequently, the new system is required to withstand all beam energies in the SPS, i.e from 14 to 450 GeV, including the previously so-called "forbidden" range, 28.9–102.2 GeV; hence, removing this limitation for the beam operation [4].

MOTIVATION

In order to reduce the local energy deposition while maintaining the total required beam absorption, several innovations have been implemented in the design of the TIDVG#5, e.g. core materials, cooling and shielding. The design was done base on the most demanding beam dump scenarios taking into account possible failures of the extraction kickers responsible to dilute the particles [4].

However, to ensure the safe operation of the system and its components, the design specifications should be guaranteed. This can be achieved by constantly monitoring the characteristics of the dumped beams, i.e. the exact position of the dumped beam with respect to the dump as well as its shape and inhibit further beam injections in case of operational problems. For this, a Beam Observation system was installed to capture an image of the particles before impacting the dump block [5] to be included in the Post-Mortem analysis that verifies the quality of each dump.

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BEAM OBSERVATION SYSTEM

A Beam Observation System, known at CERN as Beam TV (BTV), is widely used to acquire the image of the beam in all accelerator complexes. This is achieved by intercepting the trajectory of the beam inside the vacuum chamber with a screen. When the beam particles hit the screen, visible light is emitted proportionally to its local intensity. The resulting beam footprint can subsequently be observed by a detector e.g. a camera, through a dedicated view port and optical line [6].

SBDS Installation

In the case of the SBDS, a scintillation screen made of Alumina doped with Chromium (CHROMOX) is installed about 1.6m upstream of the dump shielding blocks [7]. The light produced on the screen is picked-up by a GigE digital camera from Basler [8] with a Complementary Metal–Oxide–Semiconductor (CMOS) sensor.

In order to protect the detector from the high levels of radiation produced on the dump block and to minimize the number of electronics Single-Event-Upset (SEU), the camera is installed in a low radiation area below the dump platform. In addition, it is contained in a dedicated shielding enclosure with a movable door to facilitate any maintenance access [7].

The detector's location was chosen following a set of FLUKA simulations [9] which also allowed the definition of the 17m optical line between the camera and the screen consisting of 5 high quality mirrors. The entire optical line volume is enclosed to avoid parasitic light and any damage on the mirrors and can be depicted in Fig. 2 [10].

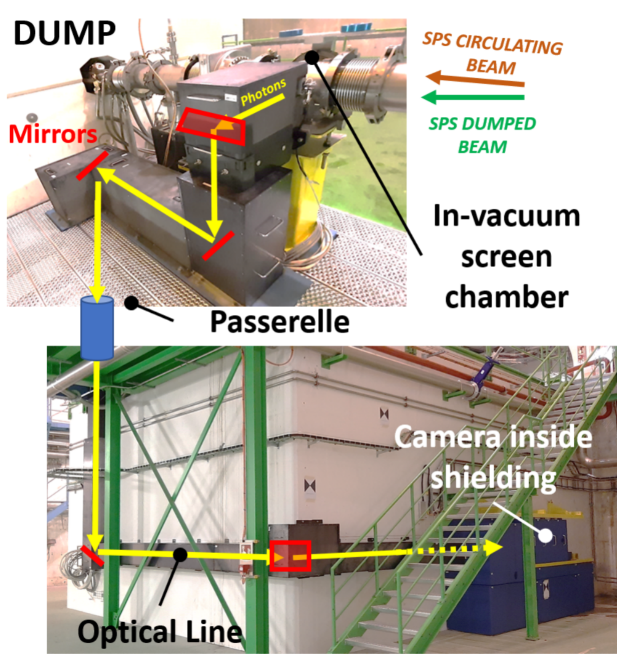

Figure 2: Optical line of the imaging system around the new SPS dump.

Acquisition System

The acquisition system at the SBDS installation is based on the relatively low decay time (> few 100 ms) of the light yield of the CHROMOX screen used. Taking advantage of the beam footprint staying on the screen for several milliseconds, the system continuously monitors the screen and selects the first image that is not saturated.

Hardware A CPU installed at a front-end computer hosts two network mezzanines, one dedicated to the communication with the camera and one for connecting the system to the control system. The camera is connected to the CPU over Ethernet through a switch and is managed by the software running in the same CPU. At the same front-end computer, a timing receiver is installed to integrate the central SPS timing to the system and custom electronics to enable the remote power management of the switch.

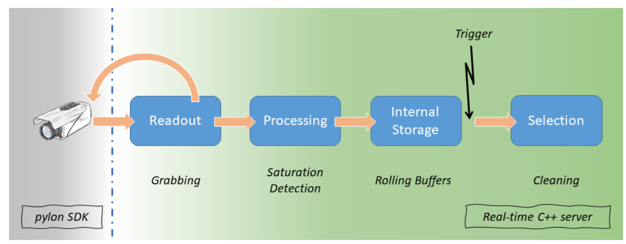

Figure 3: Image acquisition software model.

Software The real-time C++ server that orchestrates the acquisition process is designed with the Front-End Software Architecture (FESA) framework [11] and is split into two main parts:

- the *real-time* that manages the communication with the camera and its synchronization.
- the *server* that manages the communication with the clients.

The low-level access to the camera is achieved via the *pylon* Software Development Kit (SDK) [12] provided by Basler.

The image acquisition is organised in blocks that can be seen in Fig. 3. In order to improve the server's performance and avoid its blockage and consequently a potential image loss, each of the blocks run on a separate thread.

Readout During normal operation, the camera acquires images at its maximum internal frame rate, 35 Hz. The images are consecutively fed to the server by notifying the latter in the form of interrupts generated at the CPU. The server continuously grabs the new images as they arrive and copies them to intermediate storage to release the camera's buffer as soon as possible so that the camera is always ready for the next image acquisition.

Processing The copied images are subsequently provided to the analysis block for identifying if they are saturated or not. This is achieved by scanning their individual

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pixels to find the maximum value. In a saturated image, this value will be the same as the maximum value the camera's Analogue to Digital Converter (ADC) can produce, i.e. 4095 is the maximum value that can be represented by 12 bits.

Internal Storage The images are then sent to the internal storage block to be copied to one of the software's rolling buffers. The total number of rolling buffers is configurable and by default is 8 to keep the last 7 dump events in the memory. At any given time, there is an active rolling buffer that is used only for storing the images and is not available to the user. The number of images each rolling buffer can hold is configurable up to 100, split into two categories, pre and post trigger ones.

Image Selection In order to select and publish the appropriate image, the server listens to an external trigger, i.e. that the beam was dumped, via the timing receiver. This trigger enables the selection process that counts the number of images received until the rolling buffer's size is reached, before freezing it and switching to the next available one. The first image in the rolling buffer (post-trigger) that is not saturated is selected for publication and storage in the logging and Post-Mortem data base. An example of this process is depicted in Fig. 4 with the first (saturated) image in the rolling buffer on top and the sixth (the first non saturated) in the same buffer at the bottom.

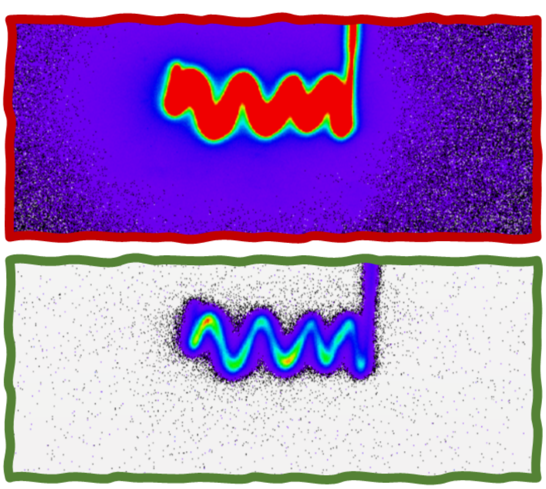

Figure 4: Example of the automatic image selection with a Fixed Target dumped beam.

Image Cleaning In order to improve the signal-to-noise ratio of the published image, an empty image, i.e. pre-trigger and without beam in the rolling buffer, is subtracted from any selected images. This process is particularly important to minimise the noise background in the published image, as light can still be present on the screen from a previous event, when two consecutive beam dumps occur relatively closely.

Image Availability Regardless of the selected image that is published, all the images of the rolling buffers, except the active one, can be retrieved before they are overwritten. This is important for verifying the aforementioned selection and cleaning mechanisms as well as the validation of the internal storage and its categorisation into pre and post trigger images.

Additionally it is also crucial during the commissioning phase of the system to set up the camera (i.e. gain, exposure time) such that it covers all SPS beam types and a non saturated image is always present in the buffers.

Internal Watchdog In order to verify the quality of each dump, the system should be 100% available so that there is always an image of the dumped beam stored for Post-Mortem analysis. The availability of the system is ensured by an internal watchdog mechanism that periodically checks and publishes the status of the acquisition and camera along with the actual image reception rate. Both statuses are subsequently monitored by the SPS Software Interlocks System [13] that inhibits further beam injections in case of anomalies.

The acquisition status is based on the image reception flagging; if they are arriving normally to the server from the camera; if there are no images arriving; or if there is an issue with their publication to the Post-Mortem database.

Moreover, the camera settings are periodically read out and checked for consistency with those expected in software. Thus the watchdog can flag if the camera status is OK, in error (i.e. having different settings) or not reachable at all.

To compliment the status publication, the mechanism includes a remote power reset of the camera via custom electronics to recover from any unexpected instability.

Operational Integration

During the SPS beam commissioning period after LS2, the Beam Observation system was validated with dumped beams varying from low intensity single bunch to trains of high intensity bunches. All features of the acquisition system were commissioned and enabled the quick setting up of the camera to cover all SPS beam types even from day 1 as they were progressively been dumped.

The system was then extensively used to commission the whole SBDS system measuring the transfer function of the kicker magnets, verifying their polarity, and assessing the effects of their potential failure.

Since the start of the SPS beam commissioning period, the system has been integrated into the operational fixed display, monitoring the SBDS status as seen in Fig. 5. The display observes various statuses of the SBDS that can be seen at the left panel. Additionally, it displays the selected non-saturated image with the dumped beam from our Beam Observation system at its center and both of the aforementioned acquisition and camera statuses on top of it. Finally, it also depicts the beam filling pattern before being dumped, at the red plot below the image.

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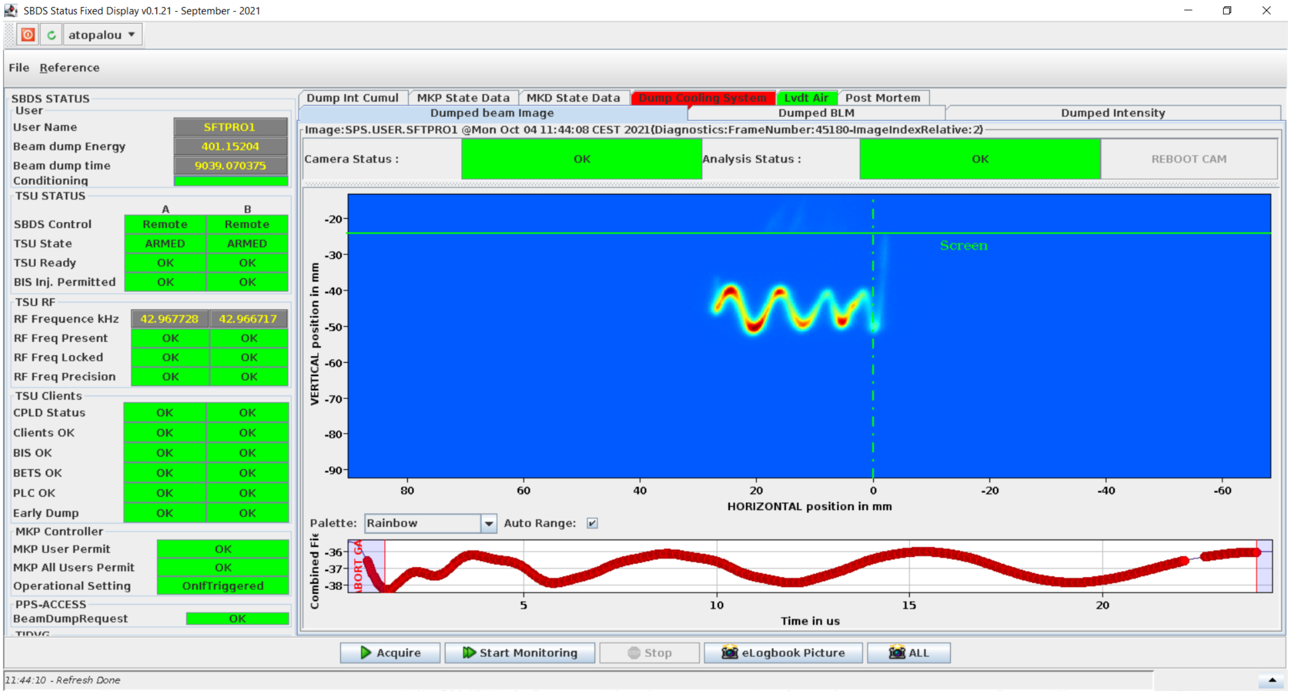

Figure 5: SBDS status Fixed Display depicting a Fix Target dump event.

CONCLUSION

In order to ensure the safe and optimal operation of the new SBDS, a Beam Observation system based on a scintillating screen and a digital camera was installed to capture and publish the image of the dumped beam.

The system acquisition is based on a free running mode, with images being acquired by the camera continuously at its maximum rate. The system integrates an *automatic detection* of the best image for publication and Post-Mortem analysis that removes the need of setting up the camera according to each beam type the SPS can produce. Additionally, it includes an *image cleaning* algorithm to improve the signal-to-noise ratio and an *internal watchdog* mechanism to monitor the statuses of the acquisition and the camera that are integrated into the SPS SIS.

During the SPS beam commissioning, the system was validated with various types of beams and was crucial in the commissioning of the new SBDS. It remains an essential part of the operational SBDS status Fix Display.

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