NEW CERN SPS BEAM DUMP IMAGING SYSTEM

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Abstract

As part of the LHC injector Upgrade (LIU), the CERN SPS is now equipped with a new Beam Dumping System (SBDS) designed to cope with the high power beams foreseen for the High Luminosity LHC (HL-LHC) era [1, 2]. Before reaching the dump, the proton beam (from 14 to 450 GeV) is vertically kicked and then diluted passing through a series of horizontal and vertical bumps. This prevents the dump damage, by reducing the power density per surface unit. The quality of each dump event must be verified, for which all SBDS parameters are logged and analysed in the so-called Post-Mortem dataset. An essential part of the verification is performed by a beam imaging system based on a Chromox screen imaged on a digital camera. The desired availability level (100%, to protect the dump) and the harsh radiation environment made the design extremely challenging. For example, it implied the need for a 17m long optical line made of high-quality optical elements, a special camera shielding (to minimise single event upsets) and a generally careful design accounting for maintenance aspects, mainly related to expected high activation levels. After giving an overview of the whole imaging system design with details on the chosen layout and hardware, this paper will discuss the DAQ and SW architecture, including the automatic, on-line, image selection for validating every dump event. This will be complemented with experimental results demonstrating the performance and reliability achieved so far.

THE NEW SPS INTERNAL DUMP

The new SPS beam dump is composed of a 5 m long absorber made of several blocks of graphite, Titanium Zirconium Molybdenum (TZM) and pure Tungsten material. It is covered by a 3 layer concrete, cast-iron and concrete/marble shielding. The weight of this assembly is 2 t for the absorber that is impacted by the beam and about 674 t for the shielding. It is located in sector 5 of the SPS machine.

To protect the block against high power density beams, the extracted protons are diluted in order to reach a non-destructive power density. The principle of the beam dumping is sketched in Fig. 1 with a simulated example of a Fixed Target type beam dump dilution shape, as expected at the front plate of the dump.

Instrumentation Specifications

The instrumentation, fundamental to the beam dump quality checks has been requested to fulfill the following main specifications:

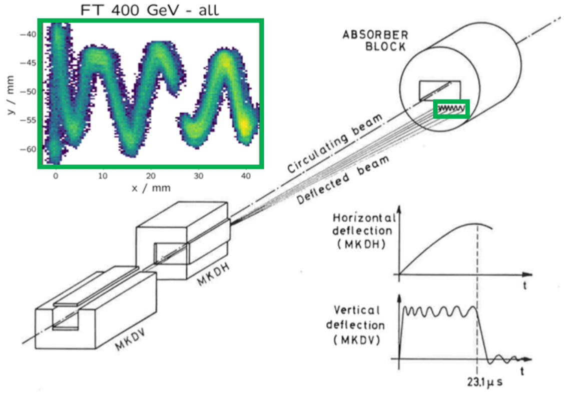

Figure 1: Principle of beam dumping and simulated example of a Fixed Target type beam dump dilution shape.

- All SPS beam dump events must be recorded. This means between $5 \cdot 10^9$ and $8 \cdot 10^{13}$ protons per event, with energy from 14 to 450 GeV.
- The imaging horizontal and vertical spatial resolution must be better than 200 µm.
- The imaging system maintenance must be optimized to cope with high radiation levels.

The design of the new SBDS monitor is based on the so-called Beam TV (BTV) system, exploited in different versions and hundreds of units, throughout the whole CERN facility. A BTV system is based on the use of a screen interacting with the beam and generating photons (i.e. different processes depending on protons energy and screen materials) that are imaged on a camera system, thus providing the proton beam footprint. In the SBDS case, the image acquisition is synchronized with the beam extraction event. After calibration, the digitized images provide an accurate beam position and size to monitor quantitatively the dilution of the beam on the dump surface. As already mentioned above, the high radiation environment has heavily affected the new BTV system design choices, from the layout (i.e. need of a

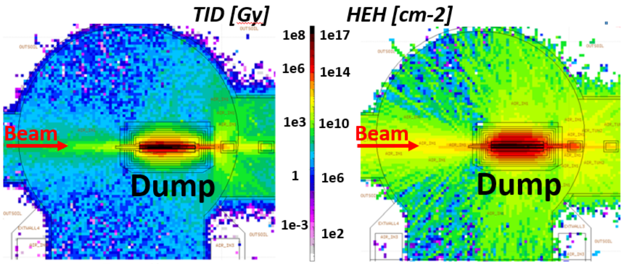

Figure 2: Fluka radiation simulations of the SBDS area showing the top view at the beam level.

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long optical line to bring the camera away from the highest radiation zone) to the selection of radiation tolerant or radiation hard components for both the optical line and the camera. Dedicated simulations (see Fig. 2) have allowed predicting up to 10 kGy total ionization dose (TID) and 1×10^{13} cm^{-2} high energy hadron equivalent fluence (HEH) at the location of the screen, about 4m upstream of the dump front plate.

THE SBDS IMAGING SYSTEM

Hardware

As imaging sensor, it was decided to use a digital camera featuring high resolution, sensitivity, gain and adjustable integration time. The harsh radiation environment discussed above yielded to the need for a dedicated optical line and camera shielding to move away and protect the camera itself. In addition, as all extractions and dumps need to be monitored, the screen is fixed, i.e. not removable from the beam trajectory.

Screen and in-Vacuum Mechanics: The worst case failure situation determined the choice of the BTV screen material. As well as the dump, the screen must withstand 100 % of the extracted beams, with a max dump rate of 333 events per hour. The predicted maximum power density of 6.5×10^{12} p/mm^2 at the screen location led to the choice of Al2O3:CrO2 (also known as Chromox [3]) as screen material, see Fig. 3. These type of screens are used at many locations at CERN with up to 1×10^{13} p/mm^2 as limit not to exceed (from heat load calculation, to remain below a temperature of 500 °C and taking some safety margin).

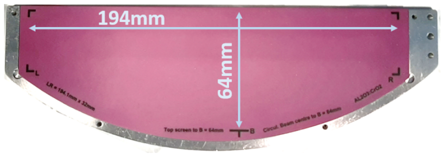


Figure 3: SBDS Al2O3:CrO2 screen mounted on its support, ready for installation.

As the dump line and circulating beam share the same vacuum chamber, the screen support design includes RF fingers in order to minimize the impact on beam impedance. A 3D drawing of the screen support is shown in Fig. 4, where the circulating beam and the vertically dumped beam are represented.

Beam Imaging Optical Line: Digital cameras [4] can be operated only in low radiation areas. Combining the irradiation results of a number of digital cameras at the CERN CHARM facility [5] (max 10 Gy TID and 1.6×10^9 cm^{-2} HEH) and a set of simulations performed to predict radiation around the SBDS zone, resulted in the decision to design a 17 m long optical line between the screen and the camera. Figure 5 shows a 3D view of the optical line integration, passing through and then around the concrete basement of the SPS dump. The optical line is based on 5 high quality mirrors carefully specified using ZEMAX Optical Studio [6] in order to minimize geometric and chromatic aberrations. Table 1 summarizes the optical line parameters, defined to achieve an optical resolution of 200 μm, horizontal and vertical.

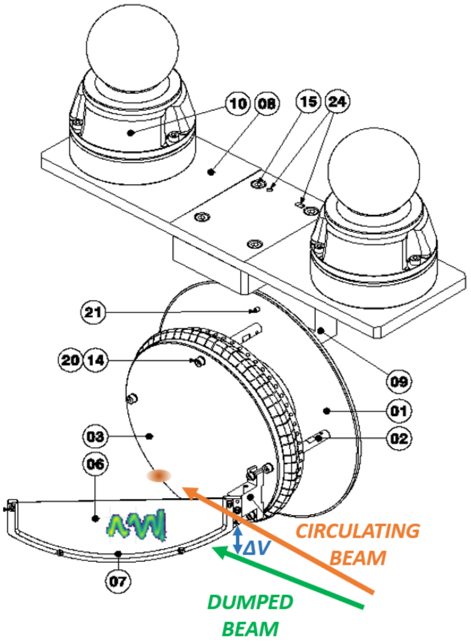


Figure 4: 3D model of the screen instrument equipped with RF fingers for impedance optimization and alignment targets.

The entire optical line volume is enclosed to avoid parasitic light and to protect mirrors from dust and bad manipulations.

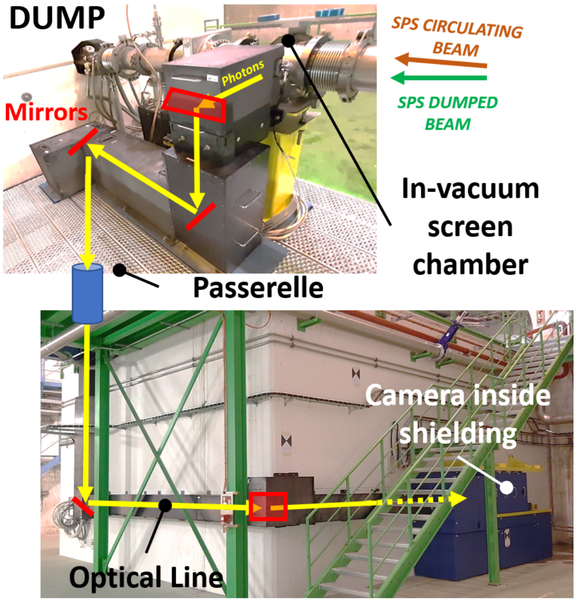


Figure 5: 3D model of the optical line of the imaging system around the new SPS dump infrastructure.

Table 1: Main Parameters of the Optical Elements Composing the Optical Line of the SPS Dump Imaging System

Length	17 m	
3x Mirror	300x200 mm^2	Flatness $\lambda/5$
2x Mirror	200x200 mm^2	Flatness $\lambda/5$
Sigma Camera lens	F600 mm	5.6NA
Basler Camera	Aca2040-35gm	73.4 dB
Spatial resolution	100 µm	
Optical resolution	200 µm	
Visibility (contrast)	35 %	

Camera Shielding: The shielding protecting the camera was dimensioned to exclude the occurrence of single event upsets due to radiation. In addition, as the radiation level imposes quite massive blocks of iron, the shielding was equipped with a movable 'door' allowing quick access for the camera maintenance without the need for transport/handling services. The shielding door is composed of 4 blocks of 900 kg each, which can be handled by a single person thanks to the use of low friction bearings. Figure 6 shows the inside of the shielding, doors open, where the optical elements for the light detection are located.

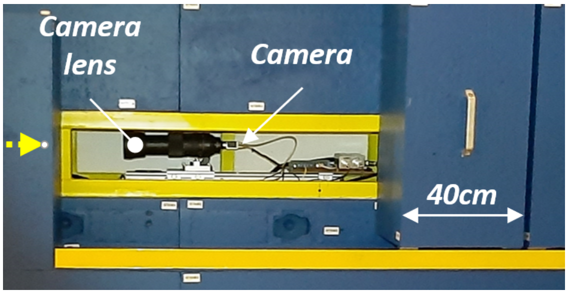


Figure 6: Picture of the shielding while open, showing the camera with its F600mm focal length camera lens.

Software

The light yield of Chromox screen decays relatively slowly (> few 100 ms) and the acquisition system is based on recording several images after each dump event. The on-line SW performs the selection of non-saturated images, with the saturation level depending on beam intensity, size and dilution strength.

Acquisition process: In standard operational mode, the camera is free running with the frame rate set at 35 Hz. All images are continuously feeding a 'rolling' memory buffer of 100 images (number of images can be set). Each dump event, seen as a trigger given by the extraction kicker (synchronous and asynchronous) will start the acquisition process by filling one of the 8 available buffers of 100 images memory space with:

- pre-trigger images from the 'rolling' buffer: used for noise cleaning
- post-trigger following images: saved for online analysis

The online automatic selection of the 1st image not saturated is first of all 'cleaned' by subtracting the pre-trigger image. This minimizes the noise background like remaining light produced by the screen, which can happen if two extractions are too close from each other. Then the image is published and stored in the Post-Mortem Data set. This image is also available for the fixed display operational GUI used by the SPS operator crew. However, all images in the 8 buffers are accessible for any processing, analysis or debugging, but they are overwritten every 8 triggers. An example of image selection is shown in Fig. 7.

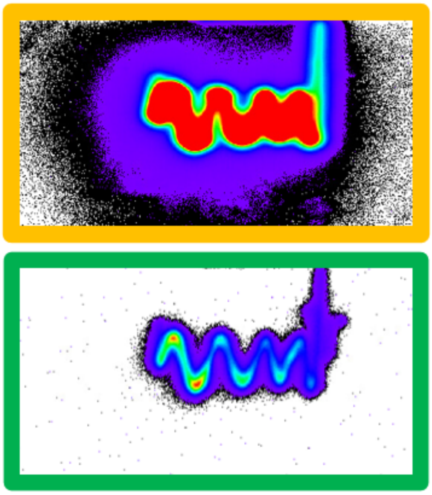


Figure 7: Example of automatic image selection. Top is first image at trigger event. Down is the first non-saturated image corresponding at the ninth image (taken at 35 Hz) after the trigger. This selected image is logged and published.

Internal Watchdog: Several checks are periodically performed to ensure the availability of the acquisition system. In particular, the software looks at:

- status of the camera and the Ethernet switch
- consistency between the settings in Front End Server Architecture (FESA) and the camera

The process includes automatic power reset sequence to recover from any unexpected instability of the system. To minimize the risk of missing beam dump events, the SPS interlock system inhibits any further beam injection, whenever the SBDS BTV system is in fault or down.

Experimental Results

Commissioning with beam: A fundamental part of the SBDS imaging system design was the choice of the camera detector with adequate integration time and gain for covering the range of beams to be measured. This, together with other features of the camera like low noise and intrinsic high dynamic range, allowed the rapid validation of the full system during the beam commissioning period. At first, with the automatic SW mentioned above to discard saturated images, the BTV system was validated with dumped beams ranging from low intensity single bunch to trains of high intensity bunches. The instrument could then be used extensively from day 1 to commission the whole SBDS system, and particularly to measure the kickerś transfer functions, to assess the effect of kicker failures and to check the polarity of the horizontal kicker designed to dilute the particle density onto the dump block. Figure 8 shows few images taken during commissioning, corresponding to dumps with different beam intensities and machine filling schemes.

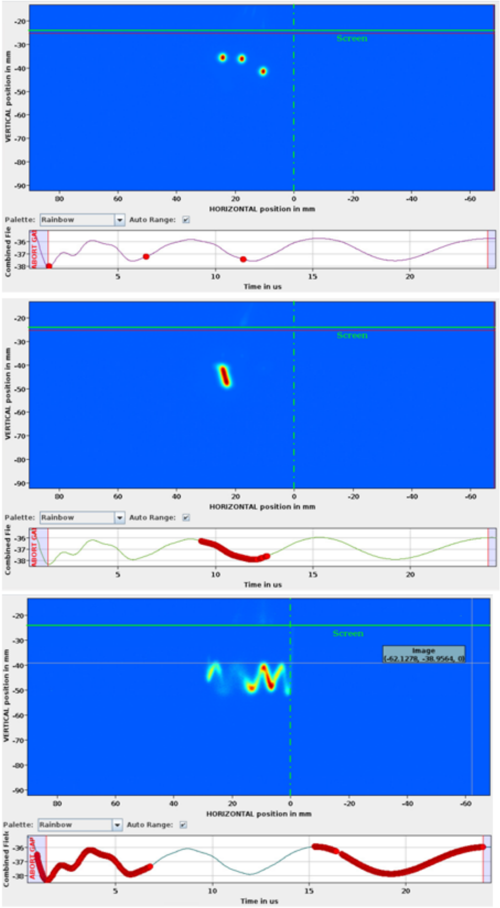
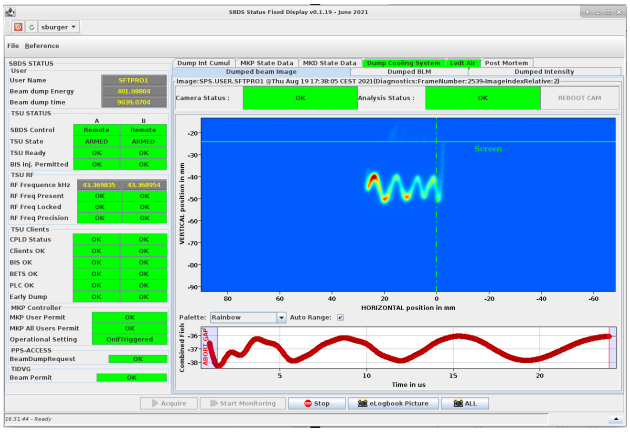


Figure 8: Examples of images taken during SBDS commissioning to confirm the good behavior of the beam extraction system, increasing progressively the number of bunch in the machine from top to bottom plots.

Normal Operation: After the full system validation during commissioning, the SBDS was handed over to the SPS crew as an operational tool to monitor and record any dump event. Figure 9 shows the operational *SBDS Fixed Display*, which includes, apart from the BTV image, a number of status, quality and sanity checks (temperatures, pressure, power, timing, etc...). This particular example refers to an extraction of a beam prepared for fixed target physics. All bunches are also displayed in red in the 'combined field' graph below the image, asserting here the SPS ring was full before extraction (the horizontal axis covers the 23 μs revolution period).



SBDS STATUS

User

User Name: SFTPRO1
Beam dump Energy: 401.08804
Beam dump time: 9039.0704

TSU STATUS

	A	B
SBDS Control	Remote	Remote
TSU State	ARMED	ARMED
TSU Ready	OK	OK
BIS Inj. Permitted	OK	OK

TSU RF

	A	B
RF Frequence kHz	43.369835	43.368954
RF Freq Present	OK	OK
RF Freq Locked	OK	OK
RF Freq Precision	OK	OK

TSU Clients

	A	B
CPLD Status	OK	OK
Clients OK	OK	OK
BIS OK	OK	OK
BETS OK	OK	OK
PLC OK	OK	OK
Early Dump	OK	OK

MKP Controller

MKP User Permit: OK
MKP All Users Permit: OK
Operational Setting: OnIfTriggered

PPS-ACCESS

BeamDumpRequest: OK

TIDVG

Beam Permit: OK

Image:SPS.USER.SFTPRO1 @Thu Aug 19 17:38:05 CEST 2021(Diagnostics:FrameNumber:2539-ImageIndexRelative:2)

Camera Status : OK
Analysis Status : OK

16:31:44 - Ready

Figure 9: SBDS Status Fixed Display showing together with all parameters required for a proper dump extraction the status of the imaging instrument hardware and the selected image of the last event.

OUTLOOK

The new SPS Beam Dump System (SBDS) was equipped with a dedicated beam imaging system, designed to monitor and qualify every single beam dump event. The instrument is based on a fixed scintillating screen in front of the dump and a digital camera as detector. The harsh radiation environment required a challenging design with the integration of a 17 m long optical line composed of 5 high quality mirrors (flatness of $\lambda/5$). The light is thus transported from the dump to a radiation shielded bunker protecting the digital camera from radiation. This monitor is a fundamental device to continuously assess the beam extraction and dump quality as well as the health of the whole system.

A new on-line image selection process was deployed to ensure the published image for *Post-Mortem* analysis is not saturated. The software also includes automatic rebooting from internal hardware and a communication status watchdog, thus minimizing downtime. This watchdog is also part of the global interlock system, ensuring that no injection occurs if the monitoring is off.

The commissioning of the SPS beam dumping system was performed from day one with the full availability of this new beam imaging instrumentation. It was then extensively used to evaluate dump kicker and diluter performance. An operational GUI is available in the control room with data showing the dilution of the beam on the dump, and work is ongoing to extract this information with machine learning methodologies to assess, together with direct kicker monitoring, the occurrence of failures.

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