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NEW BEAM LOSS DETECTOR SYSTEM FOR EBS-ESRF

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Abstract

In view of the construction and the commissioning of the new Extremely Brilliant Source (EBS) ring, a new Beam Loss Detector (BLDs) system has been developed, installed and tested in the present European Synchrotron Radiation Facility (ESRF) storage ring. The new BLD system is composed of 128 compact PMT-scintillator based BLDs, distributed evenly and symmetrically at 4 BLDs per cell, controlled and read out by 32 Libera Beam Loss Monitors (BLMs). The detectors fast response and the versatility of the read-out electronics allow to measure fast losses with an almost bunch-by-bunch resolution, as well as integrated losses useful during the machine operation. In this paper the different acquisition modes will be explained and results obtained during injection and normal operation will be presented.

INTRODUCTION

Beam Loss Detectors (BLDs) are an important part of the accelerators diagnostics. They are used during normal operation to identify and locate partial beam losses that may be caused by the malfunctioning of various devices, vacuum leaks, unexpected obstacles, misalignment, and so on. BLDs may be even more relevant during machine commissioning where this kind of problems are recurrent [1].

The European Synchrotron Radiation Facility (ESRF) is a 6 GeV light source, operating in Grenoble for more than 20 years. The facility will undergo through a major update, leading to the new Extreme Brilliant Source (EBS), in which a lower emittance will guarantee a brighter and more coherent x-ray beam [2,3]. The ESRF dismantling phase will start at the very end of 2018, and the commissioning is expected to take place between the end of 2019 and mid 2020.

Since the ESRF storage ring will still be operational until December 2018, several sub-systems which will be later used in EBS, such as the BLD system, are already under test.

The opportunity of having and testing the BLD system on the current machine will not only be a great help for the EBS commissioning, but will also allow to compare levels and loss distributions of the two machine.

NEEDS FOR THE NEW BLD SYSTEM

In order to fulfill the requirement for EBS, the new BLD system has to be able to detect both “slow” and “fast” losses [1]. This capability depends on the system dynamic range and bandwidth.

Slow losses are unavoidable and are the one that determine the beam lifetime. They are usually confined in some hot-spots and are due to the presence of collimators, scraper, septa, or other aperture limits. They also depend on the beam size and the population of the buckets, which lead to a deterioration of the Touschek lifetime. The typical time scale for slow losses is in the order of the second.

Fast losses are instead related with accidental effect, or some traumatic events such as perturbation due to injection. These losses can be distributed all around the machine, and can be visible on the single bunch or the single turn time scale.

Another constrain for the new BLD system is the limited amount of space in the EBS machine. For this reason new detectors have to be compact.

These requirements lead to the choice of PMT-scintillator based detectors, read out by a commercial Libera Beam Loss Monitor (BLM) unit [4].

BEAM LOSS DETECTOR SYSTEM

Detector

A scintillator-PMT based detector has been chosen for the new BLD system [5].

The BLD has to detect losses generated by the 6 GeV electron beam. When a high-energy electron is lost, it crashes on the vacuum chamber and creates an electromagnetic shower composed by electrons, positrons, and γ-rays. In order to detect showers, a suitable plastic scintillator can be used to convert the energy deposited by particles into visible light, which can then be detected by a commercial PMT.

The scintillator chosen is a EJ-200 rod (100 mm length, 22 mm diameter), wrapped in reflective foil to minimize the light losses. The maximum emission wavelength is 425 nm [6].

The selected PMT is a Hamamatsu H10721-110, with a cathode sensitivity centered in the scintillator emission wavelength, and a 8 mm diameter active area. The PMT requires to be powered by 5 V, and has a 0-1 V control gain [7].

The PMT-scintillator system is enclosed in a metallic casing, and an electronic card has been designed to optimize PMT power supply, gain, and signal connections. The metallic casing is also sealed to provide a first ambient-light isolation. Figure 1 presents a model of the detector.

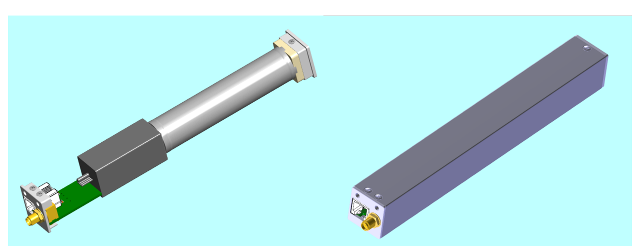

Figure 1: Model of the PMT-scintillator system without and with the metallic casing.

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In order to minimize the background signal due to the synchrotron radiation scattered x-rays, each BLD is finally covered by a 3mm lead shielding. To obtain a complete protection from ambient light, a “black hood” is added on top.

Electronics

The electronics chosen to power and readout the detectors is the Libera BLM unit by Instrumentation Technology [4], which is shown in Fig. 2. Each of these units is able to control 4 different detectors.

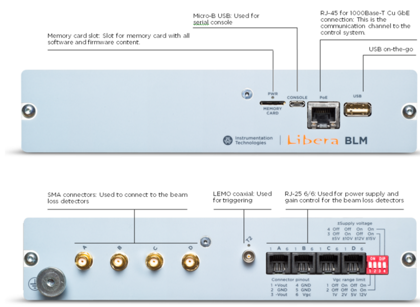

Figure 2: Libera BLM unit.

The Libera BLM is equipped with 4 independent power supplies, each of which provides the 5 V needed for the PMT operation. Four independent 0 to 1 V gain controls are also available. Power and gain are transported to the detector through RJ-25 cables.

The detector output signal can be read either on a 50 Ohm or a 1 MOhm impedance, allowing the detection of both slow (1 MOhm) and fast losses (50 Ohm). Also in this case the choice of the impedance can be done independently for each of the 4 channels.

The integrated ADC has a granularity of 14 bits. To improve the overall dynamic range, and to protect the electronics, the Libera BLMs also allow to select a different attenuation for each channel in the range 0 - 31 dB.

Each unit can be triggered by an external signal to allow the synchronization with the machine clock. The 125 MHz ADC provides a temporal resolution of 8 ns, and the data acquisition can go as fast as 10 MHz. These characteristics, together with the possibility of selecting a 50 Ohm impedance, allow the measurement of fast losses almost to the bunch-by-bunch scale. Some others features, such as the integration over one turn, or the average over several turns, are already embedded in the unit and available.

Slow losses are instead obtained integrating asynchronous data, acquired with an impedance of 1 MOhm over a long period that can also be chosen according to the machine characteristics.

Libera BLM unit can be integrated in the control system by connecting the device through another RJ-25 cable. Tango and Epics graphic control interface are available. The operative system of ESRF is Tango, and a the development of the device server and of the user application has been followed and customized by Instrumentation Technology [5].

PMTS CALIBRATION

A very useful feature of the Libera BLM is the possibility of inserting a calibration value dependent on the PMT sensitivity. This allows to obtain data which is independent on the PMTs characteristics and directly comparable.

The general data-sheet of PMTs provides an indicative value for the anode sensitivity, which may vary more then a factor 10 between different units of the same device. For this reason, each PMT comes with a specification paper indicating the real parameters for the given detector.

Moreover the sensitivity of a PMT is not constant over the long term, but may vary depending on the aging of the device.

Finally, the signal intensity also depends on the applied gain. This dependency has also to be taken into account for the data calibration.

To check both the sensitivity and the gain signal dependency of all the PMTs used for the BLD system, and to be able to repeat the calibration anytime, two techniques have been developed at ESRF: one involves the use of a blue LED, and the other a Ce137 radioactive source.

Anode Sensitivity Measurements

Data from the individual PMT specification papers shows that the average sensitivity given by the manufacturer of the 128 PMTs is 130% larger with respect to the one indicated in the general data sheet, and that the values fluctuate with a standard deviation of about 70%.

The calibration using the blue LED is done in one of the ESRF diagnostics laboratories. A Libera BLM unit is used both to control the PMT, and the LED. A metallic casing has been adapted to host a blue LED on its top. The PMT was positioned in the casing, and the signal obtained with the LED on and a PMT gain of 0.6 V was registered.

A similar procedure has been applied using a radioactive source. This kind of calibration has been performed in-situ, without need of dismounting BLDs or move them from their position inside the tunnel.

The source used is a Ce137 and is brought around the machine and attached to the metallic casing at the high of the scintillator to calibrate the whole detector. 660 keV γ-rays coming from the Cesium decay are converted into visible light in the scintillator and detected by the PMT. The signal produced by the source is measured for an applied gain of 0.7 V.

The average of the results over several PMTs has been used as reference to compare the sensitivity measured in house with the two techniques (arbitrary units), and the one given by Hamamatsu (in A/lm). Both procedures have been performed for all PMTs: results from the comparison between the manufacture sensitivity and the one measured in house are presented in Fig. 3.

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A comparison between the sensitivity given by the manufacturer (S_H), the one measured with the blue LED (S_L), and the Cesium source (S_{Ce}) is presented in Fig. 3.

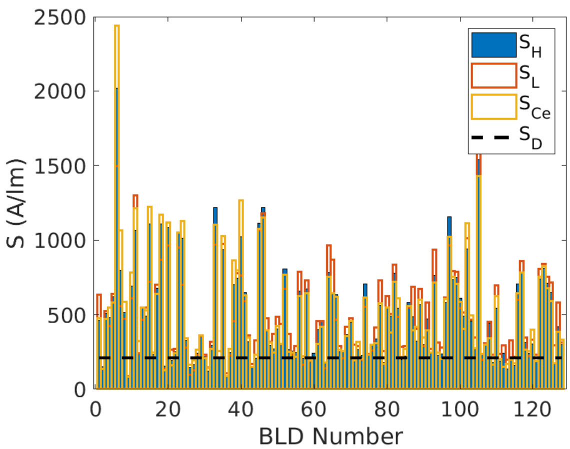

Figure 3: PMTs anode sensitivity provided by the manufacturer (S_H, blue), sensitivity measured in-house with the blue LED (S_L, orange), and with a Cesium source (S_{Ce}, yellow), for all the 128 detectors. The dashed black line is the sensitivity provided by the general data sheet (S_D).

The sensitivities measured in house are compatibles with the one provided by the manufacturer: for the LED the average of the ratio S_H/S_L is 1.06, and the standard deviation is 20%, while for the Ce137 source the ratio S_H/S_{Ce} is 1.002 with a standard deviation of 12%, as shown in Fig. 4.

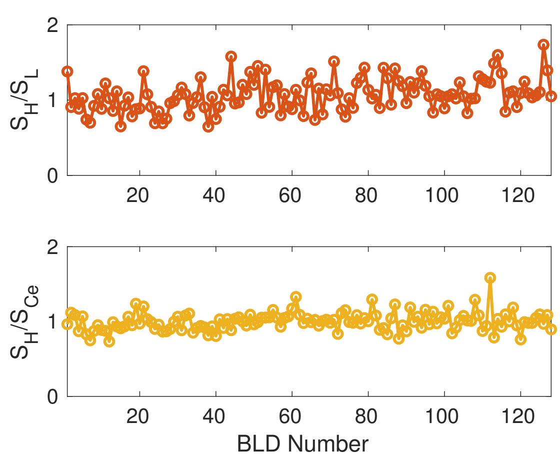

Figure 4: Ratio between the anode sensitivity by the manufacturer (S_H), and the one measured with the LED (S_L, top), and the one between S_H and the one measured with the Cesium (S_{Ce}, bottom).

Calibration application

The calibrated data SA_C are calculated according to the formula:

$$SA_C = SA \times G \times C \times A; \tag{1}$$

where SA is the raw data, G is a value which depends on the applied gain, C is the inverse of the anode sensitivity, and A is given by the applied attenuation.

In particular G ensures Independence of the calibrated signal on the applied gain. It is calculated by taking the ratio of the signal produced by a given light intensity at 0.6 V and the one produced at different gains between 0.3 V and 0.9 V . The result, presented in Fig. 5, is an average of the ratio obtained from all the 128 PMTs. In this case the LED technique has been preferred to the Ce137 source one since it covers the entire gain dynamic range.

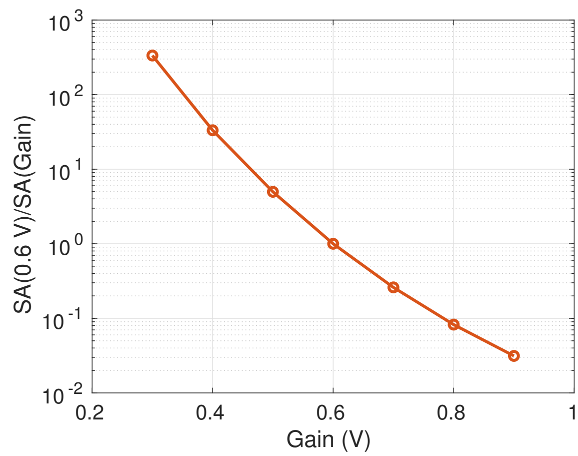

Figure 5: Ratio between the signal (SA) produced at 0.6 V and the one at different gains (from 0.3 V to 0.9 V).

LOCATION

In order to cover all the machine and obtain a consistent loss pattern, 4 detectors have been installed in each of the 32 ESRF cell, for a total of 128 BLDs. Since each Libera BLM can power and readout 4 BLDs, 32 devices have been also installed outside the tunnel.

The position of the BLDs in each cell in both ESRF and EBS is presented in Fig. 6. BLDs are located in such a way that the scintillator is at the same height of the vacuum chamber.

As a general rule, BLDs have to be located close to hotspots of the machine, such as collimators, and with a regular distribution in the different cells.

In a circular machine, BLDs are usually located on the inner side part of bending magnets: since all sources of particle losses are driven by an energy loss, particles with lower energy entering in a bending magnet will be bent more, and will more likely crash on the vacuum chamber, creating an electromagnetic shower.

The 64 BLDs from the old ESRF system are positioned according to this rule [8], and two of the BLDs of the new system have been located close to the old detectors in order to allow a direct data comparison. Another BLD has been located before the second dipole of each cell, but will be moved on the inner side of a dipole in EBS.

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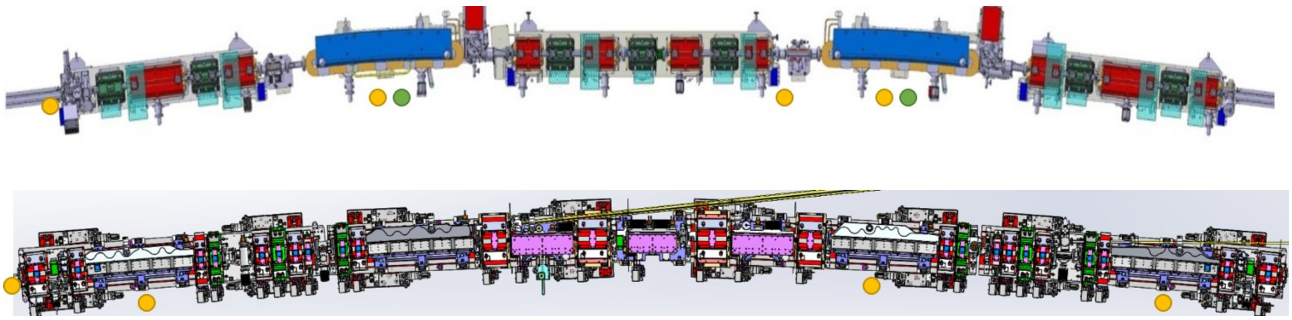

Figure 6: Distribution of BLDs in a cell for ESRF (top) and EBS (bottom). Yellow circles represent the new BLDs and green circles represents BLDs from the "old" system.

Another important part of the BLD system functionality is the monitor losses at the IDs location. The gap of an in-vacuum ID can be closed down to 5 mm, and for this reason the ID magnets are extremely sensitive to the beam losses happening upstream. IDs can in fact block and absorb these losses which may cause demagnetization.

Shielding effects due to IDs gap closure can be monitored using BLDs, and, for this reason, the first detector of each cell has been attached to the vacuum chamber of the straight section, which usually hosts IDs. Vacuum chambers of most straight sections will remain the same both for ESRF and EBS, so BLDs will almost sits in the same position in the two machines and provides comparable data.

X-RAYS BACKGROUND

The main source of background for beam loss detection, using this particular BLD configuration, is represented by the scattered synchrotron radiation x-rays. The chosen scintillator is in fact sensitive both to charged particles and γ-rays. To avoid false losses reading due to x-rays, the detector has been protected with a light lead shielding.

Tests to find out the sufficient thickness of the shielding have been performed using the machine operating in "minimal losses" condition.

Minimal losses condition can be achieved at ESRF using a 2/3-fill or a uniform filling pattern, at relatively low current ($\simeq$20 mA or lower) to obtain low-populated bunches, and high vertical emittance. In this situation the beam lifetime is very high (> 500 hours) since Touschek effects are suppressed, and losses are reduced drastically.

In general, the flux of synchrotron radiation depends from the current in the storage ring. To quantify the influence of this background on the BLDs signal, the current has been scraped from 20 to 0 mA, and slow losses from the BLDs have been registered. In minimal losses condition one would expect to see no or very weak dependency of the beam losses from the current. If this is not the case, the signal is mainly due to the scattered x-rays background.

Tests has been performed using 2 or 3 mm Pb shielding to protect the detectors. An example of the result is presented in Fig. 7: a strong dependence of the registered losses from the beam current is observed when using 2 mm of lead. In this case the effect of the losses provoked by the scraping of the beam to reduce the current is comparable with the one measured in decay mode due to x-rays. The lifetime when not scraping has always been larger than 500 hours, so this behavior of the losses cannot be related with other effect than x-rays scattering. This background is strongly attenuated when using one extra mm of lead. In this case losses due to the scraping are much stronger with respect to the background signal observed in decay mode.

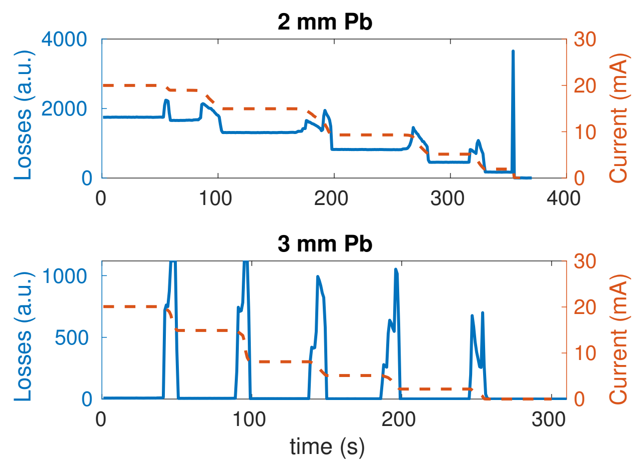

Figure 7: Beam losses (blue) measured when scraping the current (orange) from 20 to 0 mA. A strong dependency on the current is observed when using 2 mm (top), while the dependency is attenuated when using 3 mm (bottom).

These tests show that 3 mm lead shielding is enough to reduce the background due to synchrotron radiation scattered x-rays, and all the 128 BLDs have been equipped accordingly.

COMPARISON BETWEEN NEW AND OLD SYSTEM

The advantage of having an overlap between the old and new BLDs system consists in the possibility of a direct comparison between data obtained by the two independent setups.

Data from a 20 to 0 mA scraping has been registered both with the new and the old BLD systems. A scaling factor

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has to be applied in order to have comparable results. An example of losses is presented in Fig. 8. Detectors are bot PMT-scintillator based, and are located at about 50 cm one from each other. Losses have the same temporal evolution, and the same amplitude, proving the correct behaviour of the new BLDs system.

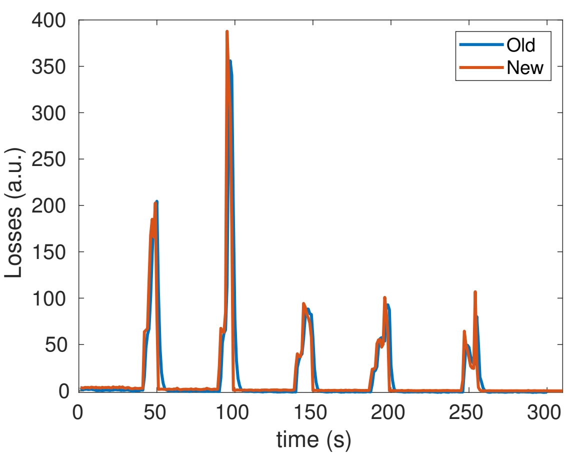

Figure 8: Comparison of losses registered during a scraping from 20 to 0 mA from an old (blue) and a new (orange) BLD.

BLD SYSTEM OPERATION

After having the 128 BLDs mounted, calibrated, and tested, the system has been put in operation at ESRF. A software application has been developed to easily monitor the loss distribution and to control all detectors from the control room. A screen-shot of the Graphical User Interface (GUI) is presented in Fig. 9.

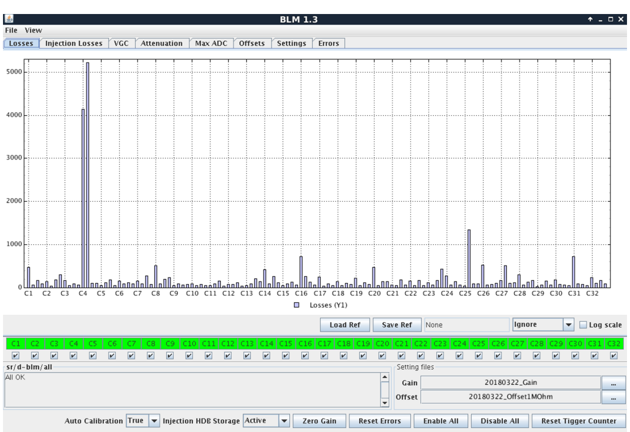

Figure 9: Application gui: slow losses are displayed during decay mode.

Auto-Gain

The application also controls an "Auto-Gain" routine, which automatically reduces the PMT gain, or increase the Libera BLM attenuation, when the signal is close to saturation.

Since the data are calibrated, the saturation level is different for each BLD. For this reason look-up tables providing the saturation level for each gain, and each BLD have been created as reference.

Operation Mode

Two different modes are available to measure loss during the user operation. The first measures the slow losses during the decay mode, and the other registers fast losses at the injection. Data are stored and are available for consultation and post-processing.

Decay Modes During the machine decay time, slow, asynchronous losses are registered at a 1 Hz rate. To do so the Libera BLM impedance is set on 1 MOhm, and the decimation level is set to 17 in order to integrate over $\simeq$ 130.000 turns. Being the revolution period of ESRF storage ring roughly 3 µs, the total integration time per acquisition is about 0.4 s.

The loss distribution is in general quite stable, specially when the machine is working correctly. Vacuum behaviour, emittance blow-ups, or the motion of some ID-gaps can induce changing in the loss distribution. Having all this data archived helps to correlate anomalous losses with one of these events.

An example of identification and localization of losses is presented in Fig. 10 and in Fig. 11. Figure 10 shows the slow losses registered by all the 128 BLDs (vertical), over 10 minutes (horizontal). The evolution looks regular, apart at about 240 s after the starting point, where some perturbations appear starting from the BLD 87 and continuing after. Figure 10 shows the detail of BLD 87, corresponding to the BLD located in Position 4 (second dipole) of Cell 22. An analysis of the vacuum in the downstream part of this Cell shows a vacuum burst exactly at the same time of the losses, which has then been recognized as the cause.

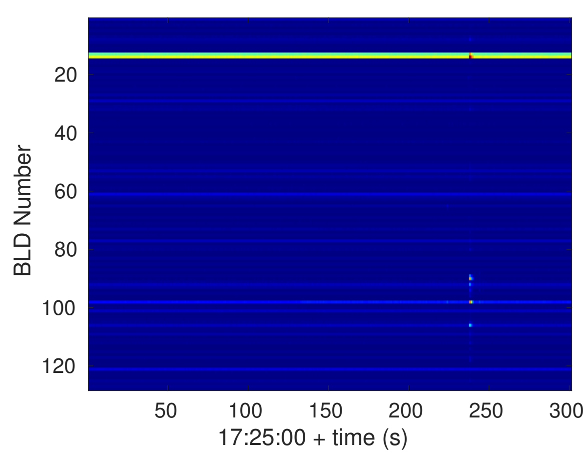

Figure 10: Temporal evolution of all the BLDs. Around BLD number 87 (Cell 22, Position 4), and time $\simeq$240 s some strange behaviour appears.

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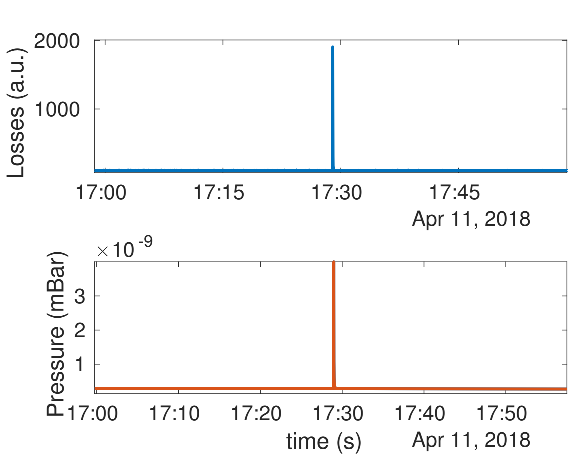

Figure 11: Correlation between unexpected losses seen by BLD 87 (Cell 22, Position 4), and the vacuum measurement in one of the penning gauge of Cell 22.

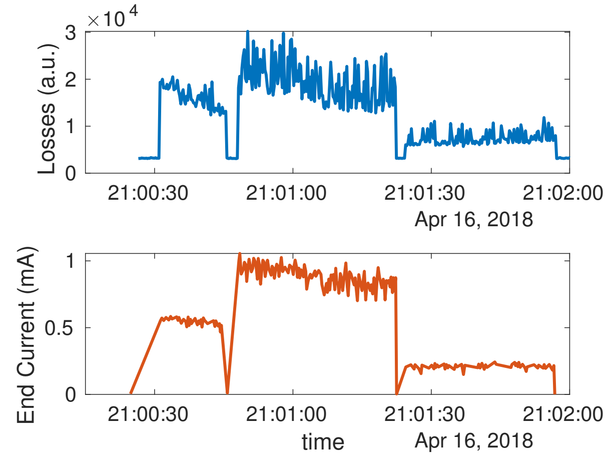

Figure 12: Correlation between losses at the injection registered from one of the BLDs (blue, top), and the one of the booster end current registered by the current transformer (orange, bottom).

Injection Mode When linac and injection kicker are on, the BLD system switches automatically to injection mode. During this phase more losses are generated, and to avoid the saturation of the BLDs fast losses are registered. The Libera BLM impedance is set to 50 Ohm, and the so called "average mode" is enabled. This mode allows to register the average of a given number of turns. In particular at ESRF, the average decimation number is set to 2, in order to obtain the average of 4 turns. Finally the integration of a buffer of 10 samples is registered.

Data are synchronous with the injection in the storage ring, with a repetition rate of 4 Hz, and are also stored at the same rate.

Injection losses are useful to study the status of the injection system and the perturbation induced. Figure 12 presents an injection during the 7/8+1 operation mode (7/8 of the storage ring filled uniformly, and a single bunch in the gap). During this mode the injection sequence foresees first the injection of two bunches, then of 4 to fill the main train, and finally of 1 bunch to fill the single bunch. This can be seen both in the injection losses evolution and in the booster end current measurement. Data from one of the BLDs and from the booster current transformer are well correlated in time.

APPLICATIONS

Apart from operational purpose, the new BLD system has several capabilities which will be useful for the EBS commissioning and other studies.

Turn-by-Turn Losses

Turn-by-Turn (TbT) losses are obtained enabling the "Sum" mode of the Libera BLM. Considering that the BLM ADC sample is 8 ns and that the revolution period of ESRF is 2.816 µs, the decimation sum has to be set to 352 to integrated over the losses produced in one turn. Being fast and synchronous losses, the impedance has to be set to 50 Ohm and the Libera BLM has to be triggered.

TbT losses will be useful during the early part of EBS commissioning, when they will complement data from BPM.

As an example TbT data, taken during the injection in the storage ring with the RF off, is presented in Fig.13. Data show that the beam is lost after about 60 turns, and that the bigger amount of the losses is concentrated in the BLD number 100 (corresponding to the position 1 of Cell 26).

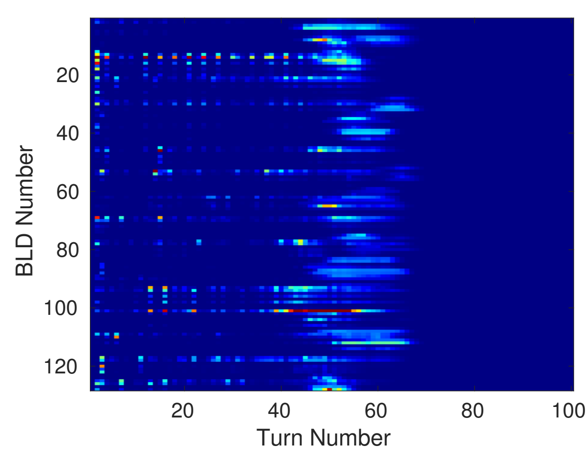

Figure 13: TbT losses with RF off. The beam preforms about 60 turns and is lost mainly close to BLD number 100 (Cell 26, position1).

Almost Bunch-by-Bunch Losses

ADC Losses provides data with a resolution of 8 ns. These are useful to observe phenomena almost at the bunch scale.

Also in this case the impedance has to be set to 50 Ohm and the Libera BLM has to be triggered to obtain synchronous data.

A typical example of bunch-by-bunch losses is given by the losses registered during an injection in "short pulse"

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mode, presented in Fig. 14 for one of the BLDs during 4 turns. In this specific example, five bunches are injected in the storage ring. Vertical grey lines in the plot represent a revolution period. After one revolution period from the trigger signal, bunches enter in the storage ring and loose some particles during the first turn, though most of the losses appear during the second turn. Not all the bunches have the same quantity of losses, this may depends on the population of the injected bunches, or on the shape of the extraction pulsed-magnet pulse.

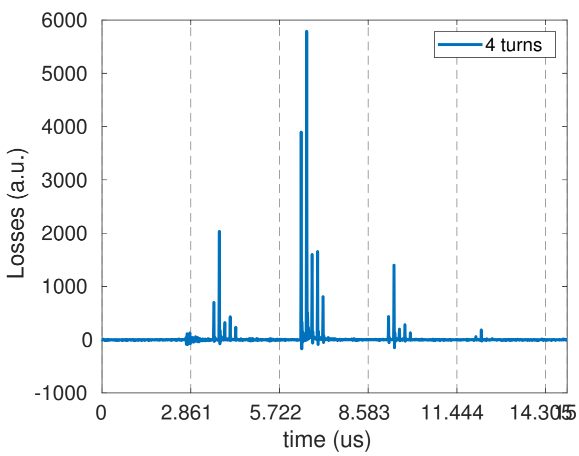

Figure 14: ADC losses during an injection of five bunches. Vertical grey lines indicate the turns. The injection happens during the second turn when some losses are registered, most of the losses appears in the second turn. Not all the bunches show the same losses.

OUTLOOK

A new BLD system is now operational to measure the losses at the ESRF storage ring. The components of the system, their characterization and the final operation applications have been presented in this proceeding. The capability of the system to measure slow and fast losses and to monitor the behavior of the machine have been proven. The new BLD system and the application developed will be installed and intensively used during the commissioning and the normal operation of the future EBS machine.

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REFERENCES

[1] K. Wittenburg, "Beam loss monitors", in *Proceedings of the CERN accelerator school*, pp. 249, 2009.

[2] *ESRF Upgrade Programme Phase II (2015-2022) - Technical Design Study*, http://www.esrf.fr/Apache_files/Upgrade/ESRF-orange-book.pdf

[3] J.L. Revol *et al.*, "Status of the ESRF-extremely brilliant source project", in *Proc. 9th International Particle Accelerator Conference (IPAC'18)*, Vancouver, BC, Canada, 2018, pp. 2882–2885. doi:10.18429/JACoW-IPAC2018-THXGBD3

[4] *BLM: beam loss monitor readout electronics*, https://www.i-tech.si/accelerators-instrumentation/libera-blm/functionalities

[5] K. B. Scheidt, F. Ewald, and P. Leban, "Optimized beam loss monitor system for ESRF", in *Proc. of International Beam Instrumentation Conference (IBIC'16)*, Barcelona, Spain, Sep. 2016, pp. 86–89. doi:10.18429/JACoW-IBIC2016-MOPG20

[6] *General purpose EJ-200, EJ-204, EJ-208, EJ-212*, https://eljentechnology.com/products/plastic-scintillators/ej-200-ej-204-ej-208-ej-212

[7] *Hamamatsu photosensor modules H10720/H10721 series*, https://www.hamamatsu.com/resources/pdf/etd/H10720_H10721_TPMO1062E.pdf

[8] B. Joly *et al.*, "Beam loss monitors at the ESRF", in *Proc. DIPAC 1999*, Chester, UK, paper IT03, pp. 3–6.