OPTIMIZED BEAM LOSS MONITOR SYSTEM FOR THE ESRF

B.K. Scheidt, F.Ewald, ESRF, Grenoble, France
P.Leban, Instrumentation Technologies, Solkan, Slovenia

Abstract

Monitoring of the 6 GeV electron losses around the ESRF storage ring is presently done by a hybrid system consisting of ionization chambers and scintillators. It allows a rough localization of the losses, but has numerous limitations: size, weight, time-resolution, sensitivity, versatility, and costs. A new system was developed consisting of a detector head (BLD) and the electronics for signal acquisition and control (BLM). The BLD is compact, based on a scintillator coupled to a small photo-multiplier module. The BLM controls 4 independent BLDs and acquires data with sampling rates up to 125 MHz Measurements performed on different configurations of BLD prototypes have lead to an optimized design that allows, together with the flexible signal processing performed in the BLM, to cover a wide range of applications: measurement of fast and strong losses during injection is just as well possible as detection of very small variations of weak losses during the slow current decay. This paper describes the BLD/BLM design, its functionality and performance characteristics, and shows results from prototypes installed in the injection zone and in close vicinity to in-vacuum undulators.

PURPOSES AND APPLICATIONS OF BEAMLOSS MONITORING

Historic Situation

The ESRF produces synchrotron light for its 40 beamlines by operating as its source a 6GeV electron beam in a Storage Ring of 844m circumference. The nominal values for the current and the emittances are respect. 200mA and 4nm (hor.) & 5pm (vert.). The typical lifetime of the electron beam is about 50hrs, meaning an electron loss rate of about 20 million/sec.

The localization of these losses is monitored & surveyed since long by different systems: A total of 64 ionization chambers of 2 different kinds, and a further set of (also 64) detectors that are based on a scintillator, optically coupled to a photo-multiplier-tube [1]. This total of 128 detectors is positioned identically in the ring structure with its 32 cells, i.e. the 4 detectors have the same position in each cell. For the bulky and heavy ionization chambers this is on the floor underneath each of the 64 dipoles, while the scintillator based detectors are placed at the beam height, radially about 40cm on the internal side of each dipole, and roughly in the middle of the dipole length. Each type of the above detectors employ a 1cm thick lead shielding to avoid detecting the inevitable scattered X-rays inside the tunnel.

Essential Diagnostic Tool in the Storage Ring

This comprehensive set of BLDs has been very helpful in the history of the ESRF in rapidly, and unambiguously, detecting and localizing any excessive electron losses. It is to be noted that the usual loss pattern does not show 128 values of roughly equal values: the loss values among these 128 units can have strong deviations due to numerous non-regular structures in the ring like e.g. the injection-zone elements (septum), scrapers, insertion device vacuum chambers with small apertures, especially for in-vacuum undulators, chambers for different modules of RF-cavities, etc.

In general, the 3 most common causes of strong or excessive losses are:

-1- Aperture-limiting effects by e.g. a miss-aligned chamber, or a non-optimum trajectory of the injected beam.

-2- A locally poor vacuum quality by e.g. a vacuum leak or a reduced conductance (e.g. a newly installed chamber with a different UHV pumping structure), or a poorly conditioned chamber (after its installation).

-3- The characteristics of the electron beam itself (variations in dynamic aperture, resonances, Touschek scattering, etc.)

These, more or less drastic, changes in the loss pattern can occur at different moments. For those mentioned under 1) it is often after installation work in the ring, so directly at the restart after a shut-down period. Those linked with vacuum leaks are obviously occurring when such leaks develop, and usually soon afterwards confirmed by the increase of the pressure gauges in the affected zone. The variations induced by beam dynamics are numerous and these variations in the beamloss readings are directly correlated with other measurements on the beam's lifetime, emittance and injection efficiency.

For all of the above uses the data rate of all these loss detectors was low, in the order of 1Hz. This speed limitation is imposed by both (some of the used) detectors, their cables for signal transmission and in particular their electronics for signal treatment and digitization. Although the detectors posses a gain control that can be set to low gain at e.g. time of injection, it is insufficient to verify that no saturation occurs in the early stage (and fast outputs) of these detectors.

IMPROVEMENTS WITH THE NEW AND OPTIMIZED SYSTEM

One of the main aims of the new system was to drastically improve the speed and bandwidth up to a time resolution of sub-orbit time (2.816us). This concerns both the BLD detector (and notably its photon-detection-electronics) and the acquisition electronics (BLM).

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For the new BLD detector it was decided to keep the concept of using a scintillator for the conversion of the products in the electro-magnetic shower (resulting from a crash of a 6GeV electron into the vacuum chamber etc.) into visible light photons, and to convert these photons into an electric signal by means of a photo-multiplier-tube (PMT). That concept had been applied in the 64 old units and shown reliable and robust behaviour during nearly 20 years of use.

Also, both the different versions of suitable scintillators and the most suitable PMTs offer the required detection speeds & bandwidth. All these components are commercially 'off-the-shelve' available. [2, 3, 4]

The other aim was to make these new BLDs much more compact than the present devices. The presently used ionization chamber based system weighs 64 Kg and have a volume of >110 litres, and the scintillator based system weighs 13 Kg with a 4 litres volume. For both systems the volume and weight is dominated by the 1cm thick lead shielding (and housing) that encapsulates the whole of the detector. In comparison, and as described here below, the new BLD detector will be less than 1 Kg of weight and about 0.3 litres in volume.

Cherenkov versus Gamma Detection

The need for lead shielding is to stop scattered synchrotron radiation being detected by the BLD. It is stressed here that these X-rays have no relation with electron losses but are continuously produced with an overall flux that is proportional to the stored current, and with a geometrical pattern in the tunnel that is strongly determined by the position of the numerous X-ray absorbers in the UHV ring which take care of the heat-load that they present.

The detection of an electron loss can be effected by so-called Cherenkov radiators that are insensitive to the above X-rays and gamma radiation. The visible light generated in such a radiator is caused by particles with mass only, which are also strongly present in the shower caused by a 6GeV electron loss. This type of detector could (in principle) have a significant advantage with respect to the so-called gamma scintillator in avoiding that additional external and heavy lead shielding. We decided to construct different prototypes based on both types of scintillators /radiators. In both cases the concept of visible photon detection was identical, i.e. with a PMT coupled to the cylindrical rod of either the Cherenkov radiator (typically quartz glass) or the scintillator. For the latter we used EJ-200, which is an inexpensive plastic scintillator that is easy to handle and can also be machined to good optical quality. We tested quartz from two different manufacturers, in comparison to the EJ-200 scintillator and also to the old perspex material used in the old BLDs with a massive volume. Such measurements were done for different thicknesses of lead shielding (for the gamma scintillators only).

The first 2 main purposes were: 1) comparing the visible light-flux produced by a Cherenkov radiator with respect to the gamma-scintillator. 2) minimizing the lead thickness for the gamma detectors without becoming sensitive to X-rays.

Another characteristic needed to be verified: the compatibility of the PMT coping with very strong light levels of ultra-short duration, typically 100ps: the length of an electron bunch. In total 4 different types of PMT were tested.

Test Bench in the Injection Zone for Prototypes

These BLD prototypes are all devices that can be installed and connected-up quickly and easily at a very suitable location : The Cell-4 injection zone. This zone offers the following possibilities and features :

-1- obtaining strong & fast losses at the time of injection during (normal user operation)

-2- creating a (very) small variation of the weak & slow losses by closing slightly a scraper in this same zone, during the normal user operation time. The sensitivity of all the prototypes is so high that such scraper induced losses were not affecting the lifetime of the electron beam.

-3- injecting different levels of beam current (from the injector) entirely & directly into this same scraper so to create massive losses and to assess the PMT's capacity of handling these more or less linearly.

We could install numerous prototypes at nearly identical positions, with only a slight displacement to avoid that one would be in the shadow of the other one. Typically a set of 4 prototypes were within 0.5 m maximum distance from each other. This allowed a direct comparison of their results and behaviour under identical conditions of imposed beamlosses. Any modifications to be made (e.g. changing the thickness of the lead shielding) could be done at a weekly basis, during the usual day of accelerator maintenance with tunnel access.

Main Conclusions of Tests for and Optimized BLD

The flux produced by the Cherenkov radiators was at least one order of magnitude below that of the EJ-200 scintillators (for comparable volumes).

Also, the 2 mm thick lead shielding proved sufficient to be immune against the scattered X-rays, provided that (known) hot points of such scattering are avoided for the location of the BLD.

Consequently, we see no advantages of pursuing a Cherenkov based BLD since the (quartz) material is more expensive while less sensitive, and the only 2mm lead shielding has little impact on the size, weight and compactness of the final BLD.

The 4 PMTs under test showed important differences in coping with very strong & ultra-fast losses. The PMT module of Hamamatsu H10721-110 offered a satisfactory behaviour in both regimes of extreme uses like fast and strong losses (with the PMT connected to a 50 Ω impedance) and the slow and weak losses (now connected to a Hi-Z load).

It is finally remarked that the 425 nm of peak-emission in the spectra of the EJ-200 scintillator is well suited for the photo-cathode characteristics of the PMT.

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Other Aspects of Optimizing the BLD Design

The sensitivity depends on the volume of the scintillator/radiator and then the efficiency of transmitting these generated visible photons to the photo-cathode of the PMT. The H10721-110 device has an 8mm circular area of the effective photo-cathode. Coupling the light produced in a cylindrical rod of 100 mm length and 22 mm diameter with a maximum possible efficiency to a window of only 8 mm needed a suitable adaptation. But the assessment of the efficiency of the various possible configurations needed an experimental determining that was done by exposing these different configurations to a radio-active source (Cesium 137, 600 KeV gamma emitter) at close distance. For each configuration we used the same EJ-200 material and a calibrated PMT. This method allowed us to also detect that the quality of the surface finishing of the rod is very important.

These tests concluded that wrapping the rod in highly-reflective aluminium foil, on all sides except the 8mm diameter on the face in contact with the PMT, was the most effective way of optimizing the sensitivity.

ELECTRONICS FOR THE CONTROL AND SIGNAL ACQUISITION (BLM)

The BLDs' output signal is sent over a standard 50 Ω coax cable. This is typically a unipolar pulse or train of pulses with negative polarity in the case of fast/strong losses, or a rather weak and close to DC signal in the case of slow/weak losses without any rapid variations. It is important to set the input impedance to 50 Ω in case of measuring these fast/strong losses (at e.g. injection) while the Hi-Z impedance is much more suitable for the weak/slow loss measurement. The BLM device offers the possibility to acquire the signals of 4 BLDs (see table 1). Each of these 4 input channels can be configured fully independently for input impedance and for analog gain. For the analog-to-digital conversion a DC-coupled dual-channel 125 MHz ADC with 14-bit granularity is used. The sampling frequency is configurable within a 80-125 MHz range and common for the 4 channels, as is a trigger signal that defines the start of buffer filling.

Table 1: Hardware Properties of the BLM

Property	Description
Input channel connector	SMA-female
Max. input amplitude	±5 V CW at 50 Ω ±1.25 V CW at 1 MΩ
A/D converter	14-bit, dual channel
Sampling rate	80-125 MHz
Measurement bandwidth @ 50 Ω input termination	35-50 MHz depending on signal amplitude
Variable Attenuation	31 dB, 1 dB step
Trigger input	LEMO, LVTTL

The ADC-buffers (up to 1 mega-samples in size, is ~8ms) are the fastest data available with 8 ns time resolution (when at 125 MHz sampling). The limitation of the analogue bandwidth to 50 MHz is still fast enough to clearly detect and measure losses of individual bunches when in e.g. the 16 bunch filling mode with 176 ns separation between these bunches (=22 ADC_samples).

In many cases the user wants to obtain information of the losses on a different (slower) time-scale, e.g. at turn-by-turn rate. In that case a SUM buffer is available in which the sum of a user-defined number (SUM_DEC) of ADC samples is stored. In the case of the ESRF this number is set to 352 (352x8 ns=2.816 us=orbit revolution time). An additional so-called ADC_mask makes it possible to define a window on the raw ADC data in which only samples within this mask are summed-up in that SUM buffer. This allows to precisely put a time-domain filter on e.g. a single bunch in the ring and to effectively measure the turn-by-turn losses of that bunch only.

Data samples from the SUM buffer are additionally averaged and stored to the AVG buffer that is again conveniently configurable with a selectable decimation value (AVG_DEC). All the above buffers need either a trigger signal, or can be self-triggered by setting a threshold level on the input signal that is continuously monitored for detecting a signal above that threshold and then subsequently starting the filling of the buffer(s).

In addition to these triggerable buffers there is also a continuous data stream (SA_stream) available with its selectable SA_DEC parameter.

In addition to the here above type of 'integrating-mode', the processing in this BLM device offers a 'counter-mode' : the ADC data is continuously processed and checked for the "count" threshold. Every ADC sample that exceeds the count threshold increments the counter value. The "data rate set" parameter specifies the read interval (e.g. 0.1 second). It subsequently results in a 'Counter stream', as shown in the upper part of the below Figure 1.

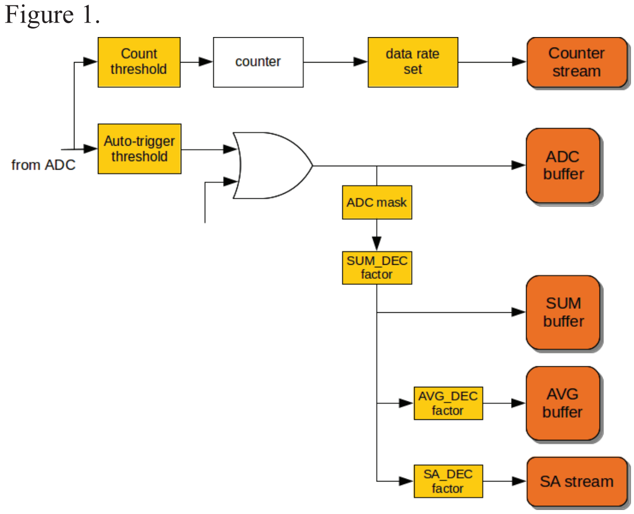

Figure 1: Numeric processing modes in the BLM.

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To make the combined system of BLD and BLM as simple and straight-forward as possible in its practical installation and use, the Libera BLM can provide the power supplies and gain control signals to each of the 4 BLDs. The maximum output current per channel (power supply + gain control) is limited to 30mA. Power supply voltage can be selected by a dip switch (±5, ±10, ±12, ±15 V). The gain control voltage can be set with 12-bit granularity through the software interface. The limit is still set by a dip switch (1, 2, 5 or 12 V). Connections between the BLM and the 4 BLDs are made with the low-cost RJ-25 6p6c connectors and with a 6-wire cable. The BLM instrument itself is powered by Power-over-Ethernet (consuming less than 15 W in total).

This BLM acquisition and control electronics was developed in cooperation with the Instrumentation Technologies company and realised by them and is now commercially available under the name Libera-BLM [5].

The detailed functionalities were defined by the ESRF and then implemented in the Libera BLM's FPGA and CPU. The top-layer interface is TANGO compatible.

RESULTS AT INJECTION

The BLD prototypes have been tested under numerous conditions of the stored beam in the storage ring, and very different conditions of the injected beam. Initially we only had these prototypes in the injection zone, but later we installed 2 units each just down-stream two different in-vacuum undulators (ID27 and ID31). Examples of the fast data that they yield at injection are shown in the below Figures 2 and 3. The ADC buffer shows the strongly varying loss level of the 5 injected bunches, within one turn, and from turn-to-turn. The vertical scale is mV and the horizontal scale in samples (at 125MHz, meaning 352 samples per turn (green lines), and 22 samples between the bunches).

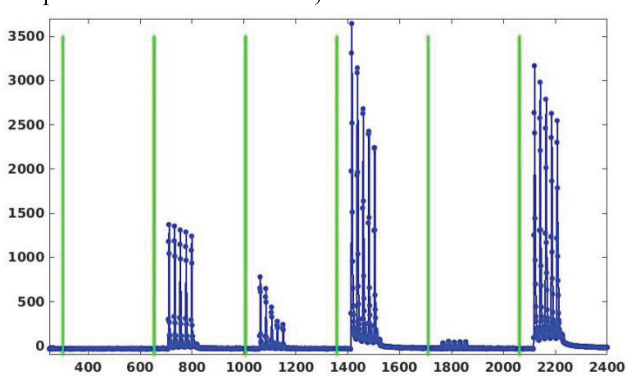

Figure 2: The ADC buffer at injection, showing the injection of the 5 bunches over 6 consecutive turns.

The SUM buffer shows losses at orbit-turn sample rate and allows seeing the signature of phase and energy oscillations of that injected beam. By a change of 30 degrees (red-curve) with respect to the nominal value (blue) the time structure of the synchrotron oscillations appears with a stronger amplitude.

The above results are obtained with a moderate gain (GCV) setting of the PMT, typically 0.5 V for 1 V maximum, so still offering an increase of sensitivity by two orders of magnitude.

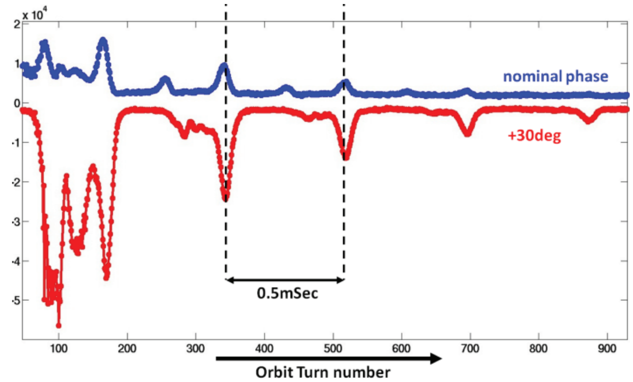

Figure 3: BLD signal at injection, with injected beam at 2 different phases: blue = nominal, red = -30 (plot inversed)

CONCLUSION AND PROSPECTS OF FULL INSTALLATION IN 2017

The optimized beam loss detector system of the ESRF is based on an EJ-200 scintillator rod of 100x22mm, coupled to a compact PMT-module and housed in a 190x25x25mm simple housing with convenient SMA and RJ-25 connectors. It is a low-cost device with compact dimensions that allows a straight-forward installation in various locations in the ring tunnel, also at points with limited access or free space.

The BLD device is capable of both detecting and transmitting the fast signals caused by fast losses at e.g. injection, and detecting very small variations of losses. In both cases the transmitted signals are fully exploited by a performing and versatile acquisition (Libera-BLM) with flexible digital signal processing and also providing the full control of power supplies and PMT gains for the four BLD units.

The ESRF is now procuring about 160 of such BLDs and 40 associated BLMs for their signal acquisition and control. They will be installed progressively from early 2017 onwards in the present storage ring to gain full experience with them in all modes of use and functionality in the two remaining years before dismantling that storage ring. They will then be recovered (early 2019) and re-installed for the new EBS storage ring to provide an essential tool in the commissioning of EBS (early 2020) and well beyond.

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