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BEAM INSTRUMENTATION PERFORMANCES THROUGH THE ESRF-EBS COMMISSIONING

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Abstract

The upgrade of the European Synchrotron Radiation Facility (ESRF) storage ring has lead to the construction of a new machine called the Extremely Brilliant Source (EBS). EBS has been successfully commissioned in less than three month and reached the targeted parameters for user mode. The success of the EBS commissioning also depended on the performances and the reliability of the beam instrumentation used to monitor the beam. In this paper a summary of the EBS commissioning is presented with a special focus on the beam instrumentation performances.

INTRODUCTION

After one year of shutdown during which the old ESRF storage ring has been completely dismantled, the new Extremely Brilliant Source (EBS) has been successfully commissioned and it is currently running in user mode.

The innovative Hybrid Multi-Bend Achromate lattice allows to achieve horizontal and vertical emittances of respectively 150 and 5 pm [1]. Thanks to the reduction of emittances, in particular in the horizontal plane, the 6 GeV electron beam is able to produce a more brilliant and coherent synchrotron radiation beam.

User mode beam parameters have been reached in three month.

The commissioning started on November 28th 2019, few days ahead of schedule thanks to the time saved in the installation phase and the quick commissioning of the linac and the booster. The first turn was achieved straight away thanks to the outstanding work done on the machine alignment. The beam was stored for the first time on December 5th with on-axis injection. In this period two obstacles were found and removed and problems related with magnets calibration and cross-talking were spotted and solved. On December 15th off-axis injection was established and accumulation occurred. After one moth shutdown on January 17th 2020 the commissioning started again and it ended exactly on time on March 2nd when 200 mA were achieved and the hand was let to the commissioning of beamlines.

The whole commissioning period can be divided into two main phases:

- First turns and storage;
- Accumulation and current ramp-up.

These results have been quickly achieved also thanks to a well functioning beam instrumentation system which has been able to monitor the beam from day one. Most of the commissioning work for the beam instrumentation in fact was performed on the old ESRF machine, as presented in [2].

In this paper, the performances of the main beam instrumentation systems and their relevance in reaching each of the milestones will be presented.

BEAM POSITION MONITORS

The EBS Beam Position Monitor (BPM) system is composed by 320 BPMs blocks (10 per cells) equipped with a hybrid Libera electronics system for data acquisition and processing [3]. This hybrid readout system is composed by 6 Libera Brilliance, capable to provide stream of data at 10 kHz which are used by the Fast Orbit Feedback, and 4 Libera Spark.

The BPM system was essential during the commissioning not only for orbit measurements and for allowing the machine tuning but also to see the beam during first turns at very low current, thanks to its high sensitivity.

First Turns and Storage

During this phase, BPMs were used mostly in ADC or in Turn-By-Turn (TBT) mode. Liberas Spark naturally work in time domain processing: this makes it rather easy to switch the system to TBT mode. For Liberas Brilliance the anti-smearing algorithm has been used to reduce the effect of the narrow digital filter embedded in the electronics [4].

For the first turns, the most used feature of the BPM system was the the signal “Sum” providing the sum of the signals coming from the four BPM buttons. This signal is proportional to the current and a plot of the its value versus the BPM number provides a clear indication of the presence of the beam along the machine. The intensity of the signal being proportional to the current, a drop of the of intensity represents a drop in current: this feature can clearly reveal the presence of obstacles on the trajectory.

Figure 1 shows one of the first injections in the storage ring during November 28, first day of commissioning. The horizontal axis corresponds to the Libera ADC samples: 304 samples represent one revolution period. On the vertical axis, the BPMs are shown ordered in the direction of the beam propagation: one column represents one machine turn. The data is triggered 7 revolution periods before the beam arrival time. It is clear that the beam was able to perform more than one turn, already at the first injection. Also, it is possible to notice that a drop of beam intensity is present somewhere around 2/3 of the machine (cell 23). This was the first identification of the presence of an obstacle in the

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storage ring, which indeed was confirmed by other systems and removed straight after.

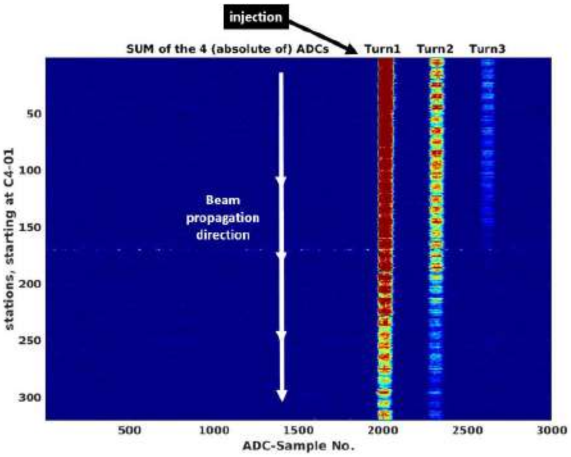


Figure 1: One of the first injection in the EBS storage ring, seen by the BPM system in ADC mode. One turn corresponds to 304 ADC samples, the beam is moving from the top to the bottom.

The BPM system has also been able to measure the beam first turn trajectory from day one. Figure 2 shows the orbit of the beam over the first two turns (one turn corresponds to 320 BPMs). Due to the large excursion of the beam path, a polynomial model has been used to obtain the transverse beam position online instead of the standard Delta-over-Sum formula [5].

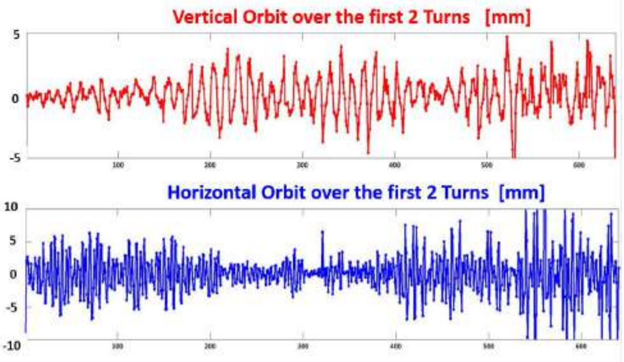


Figure 2: Horizontal and vertical orbit over two turns during one of the first injections in the EBS machine.

Beam orbits obtained in this way have been used since the beginning to compute and implement corrections and adjust the machine parameters.

The BPM sum signal has also been used as rough, not calibrated, turn-by-turn current monitor when trying to store the beam via RF capture. The sum turn-by-turn signal from one of the BPM was used to spot the number of turns performed by the beam. When RF-capture happened the signal did not go back to the noise level but stayed higher, as shown in Fig. 3.

Moreover, the injection efficiency was very low at the beginning, only a small amount of electrons was entering in the storage ring and the standard current transformer was not sensitive enough to measure such a small current. To cope with this lack of information, slow data from BPM sum signals was displayed at a sampling rate of 1 Hz and this allowed to see the first stored beam even if its current was lower than 1 µA.

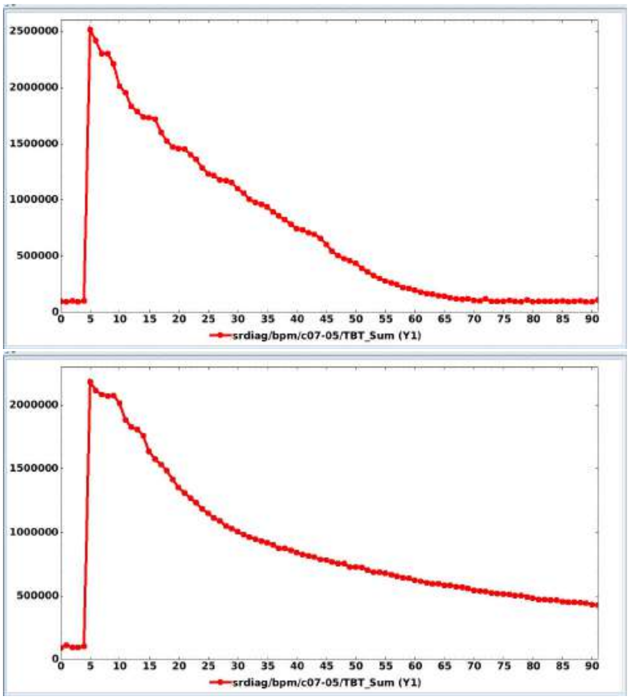


Figure 3: Turn-by-turn sum signal from BPM 5 of cell 7. Each sample represent one turn. No RF-capture (top), beam stored (bottom): the signal stays on top of the noise level.

Accumulation and Current Ramp-Up

Throughout all the process of achieving accumulation and then current ramp-up, BPMs have been constantly used to measure the orbit before and after applying corrections.

In order to guarantee a better precision, Beam Based Alignment (BBA) has been performed as soon as 5 mA of stored beam were reached. The rms of the offsets yielded values of 170 µm on the horizontal plane and 142 µm on the vertical.

The vertical beam stability measured with 20 Hz SA data was found to be 32 nm without orbit correction and it went down to 12 nm (rms) when corrections were applied.

Orbit measurements using the optimized BPM system were able to spot problems with the scale factor of lattice magnets, calibration errors, unexpected magnetic cross-talk between quadrupoles and dipoles. Of course, these measurements are still very important even after the commissioning period, in order to permanently monitor the beam and to provide an input to the feedback system.

BEAM LOSS MONITORS

In 2018, an upgrade of the ESRF Beam Loss Monitor (BLM) system has been performed [6]. The system was installed and fully commissioned with the old machine.

The EBS BLM system is composed by 128 Beam Loss Detectors (BLDs, 4 per cell), and 32 Libera-BLM electronics (1 per cell), each one capable of control and readout 4 detectors. The BLDs are calibrated relative to each other to ensure consistency between the readings of different units.

The BLM system has been of great importance during all the commissioning, mainly thanks to its high sensitivity and its versatility in acquiring easily fast and slow data. The fast-data configuration has been mainly used during the First turn phase, while the slow data acquisition has been of great help to monitor the vacuum conditioning and for machine optimization.

First Turns

In order to obtain useful signals, during this phase, the BLM system was set in "Fast acquisition" mode. In this mode, the electronics input impedance is set to 50 Ω in order to be able to acquire almost bunch by bunch losses. Two possible operation settings could be selected and could be checked in parallel:

- ADC mode: raw data from the ADC at 125 MHz;
- Turn by turn: sum of the ADC signal in order to integreat the losses in one turn (≃333 kHz).

The ADC data has been used since the first moment to spot the real number of turns the beam was performing. It is natural that during first injections the beam get lost. The most of the losses will be concentrated in the first turns but the residual beam will continue circulating for longer. This could be easily observed using one of the BLDs and looking at ADC data comprehending a temporal span of several turns, as shown in Fig. 4. The raw ADC data from one of the first injection showed that most of the beam was lost in the first 3 turns, here the beam still provided enough signal to be seen also by the BPMs (Fig. 1), but some more turns were actually performed.

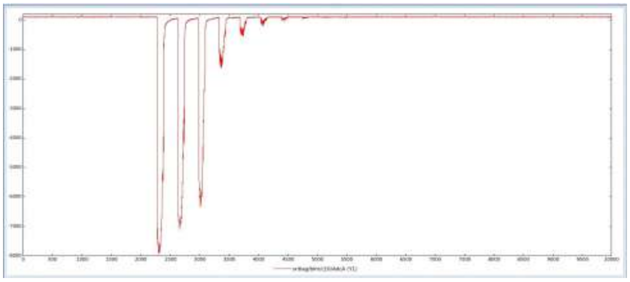


Figure 4: ADC data of one of the first injections (as in Fig. 1), showing that the beam actually performs more than three turns.

With the BLM system being distributed all around the machine (as the BPM system), it was possible to follow the longitudinal position of the beam and spot the location in which it was mainly lost. Since the very first injection it was in fact clear that the beam was performing more than one turn and that it was mainly lost before the first BLD of cell 23, i.e. at the straight section. This, together with the data from the BPM, made clear the identification of the first obstacle that was found in the storage ring. Figure 5 shows the distribution of losses at the first turn, peaking at the first BLD of cell 23.

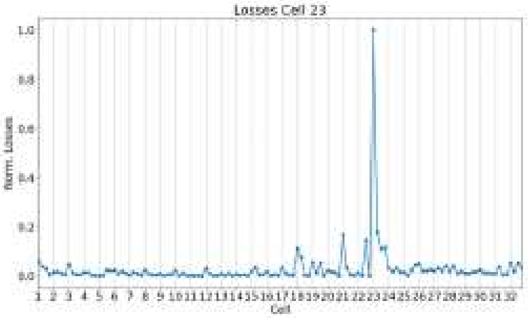


Figure 5: Distribution of the losses of the first turn of one of the very first injection in EBS. The losses are concentrated at the first BLD of cell 23.

In the same way, a mis-installed vacuum vessel in cell 8 and a second obstacle in cell 5 have been identified.

The obstacle in cell 5 was the reason for the low initial injection efficiency. Cell 5 is in fact the first cell after injection (happening in cell 4). A small residual aluminium foil was trapped there generating some losses some turns after injection. The amount of losses on turn by turn base was not so high after few turns though and nothing clear was observed neither by the BPM system. However, after storage, when switching the BLDs to slow acquisition mode, a huge spike was observed in cell 5. In order to verify the presence of an obstacle, bumps at the supposed obstacle location were performed, showing a clear indication of its presence, as depicted in Fig. 6. The removal of this obstacle drastically improved the injection efficiency allowing accumulation and current ramp-up.

Current Ramp-Up

The BLM system has been heavily used during the current ramp-up phase for two main scopes: machine optimization and vacuum conditioning monitoring.

In the first case the sum of the slow signal (1 MΩ impedance, 1 Hz repetition rate) has been used to optimize the beam lattice: a reduction of the signal (i.e. total losses) is related with a better configuration of the machine at a given emittance. This signal has been preferred to the one of the lifetime, used for the old machine, being more sensitive and responding faster to the setting modifications. An example of optics optimization using the total losses is presented in Fig. 7: during the beam decay, the lattice was tuned in order to minimize the losses maintaining the emittance constant.

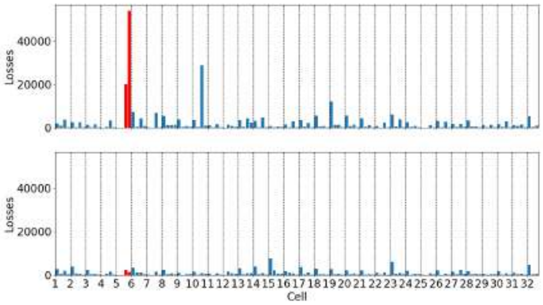


Figure 6: Slow losses around the ring before (top) and after (bottom) the bump in cell 5. The peak reduction due to the bypassing of the obstacle is evident.

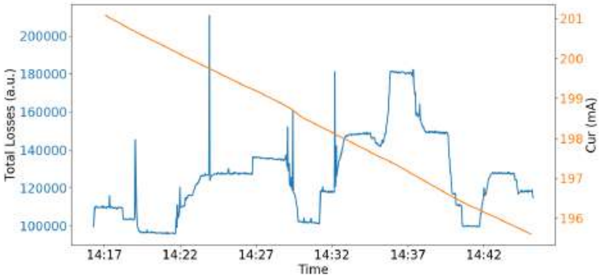


Figure 7: Total losses used to perform beam optimization (in blue) and beam current (in orange).

The other main usage of the BLM system during the commissioning was the monitoring of the vacuum conditioning especially at the insertion device chamber positions. These chambers are typically very small and constantly heated by synchrotron radiation and thus degassing at least during the first period of exposition. Also, a small misalignment of the chamber might result in damages due to the high flux of hard X-rays impinging on the chamber surface. The expected behavior is a reduction of losses after some time of vacuum conditioning at a given current. Mostly, this has been the behavior of all the insertion device chambers but two that were promptly replaced. After chambers were removed the normal conditioning behavior of the machine was recovered.

ELECTROMAGNETIC DEVICES

Electromagnetic devices such as current monitors and striplines have been very useful during machine commissioning. In particular, a large use of striplines to monitor the fill pattern and for tune measurement have been of great help.

First Turn

The fill pattern monitor system, developed in the old machine [7], guarantees a high dynamic range and a good bandwidth. To see the first turn, attenuators connected to the stripline used as pickup were removed in order to extract the largest possible signal. This indeed allowed to see the presence of beam since the very beginning of the commissioning. Figure 8 shows a snapshot of the fill pattern over several turns during one of the very first injections. The injected fill pattern was 1/3 of the storage ring and it is clear that the beam current was reducing after each turn.

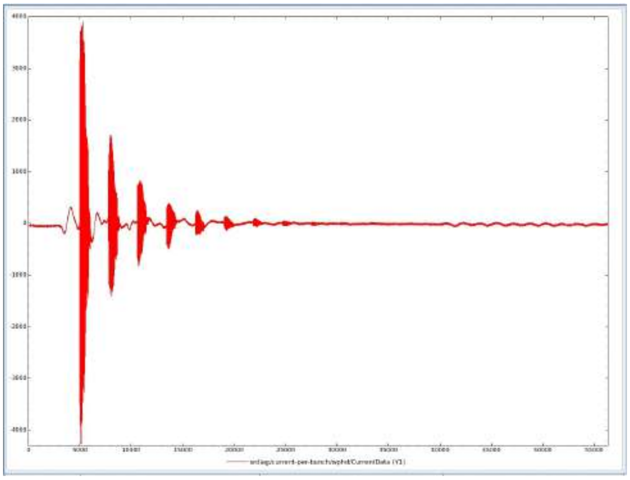
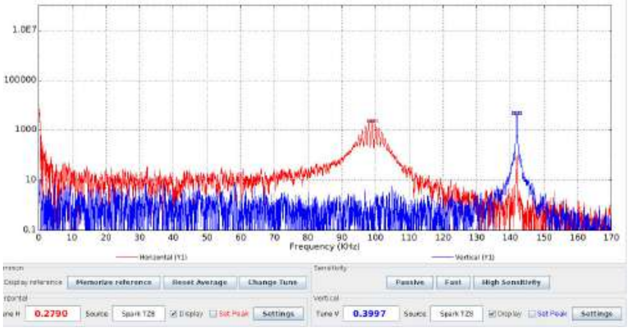


Figure 8: Snapshot of the device server of the oscilloscope used for fill pattern measurement during one of the very first injections.

As soon as the beam was stored the tune monitor started to be of great importance. At EBS, the tune monitor system [8] consists of a shaker to excite the beam, four BPM buttons from one of the 20 button chambers, a Libera Spark to read the data and a device server for data processing. Attenuators used to reduce the signal intensity were removed for in order to be able to perform measurements at very small current.

A snapshot of the tune monitor application obtained the first day of stored beam is presented in Fig. 9. Note that the estimated current at that moment was 50 µA.



une H 0.2790 Source Spark TZ8 ☑ Display ☐ Set Peak

Tune V 0.3997 Source Spark TZ8 ☑ Display ☐ Set Peak

Figure 9: Snapshot of the tune monitor application. In red the horizontal tune and in blue the vertical one.

Current Ramp-Up

During the current ramp-up, the tune monitor and the fill pattern measurements have been used in a standard way to routinely monitor tune and fill pattern. In particular this last one has been used also to check the synchronization between

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the injector and storage ring, such to verify the timing and improve the injection efficiency.

Once accumulation was established standard current monitors as the Parametric Current Transformer (PCT) and the Integrated Current Transformer (ICT) have been successfully put in operation showing outstanding resolution. Figure 10 shows the beam current over two days just after accumulation was established. In order to condition the machine the maximum amount of current was let circulating into the machine during night, while during day-time, commissioning work was carried out.

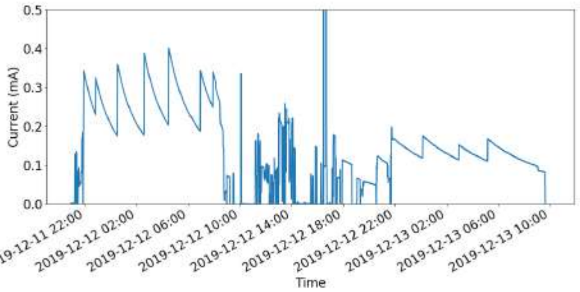


Figure 10: Current evolution during two days just after accumulation was established.

FEEDBACK

Feedback systems are used to improve beam orbit stability (orbit feedback [9]) and avoid coupled-bunch or single-bunch instabilities (bunch-by-bunch feedback [10]). Both systems were developed and commissioned on the old ESRF storage ring.

Current Ramp-Up

The orbit feedback consists in a mixed slow-fast feedback. The orbit perturbations were already minimized by the machine design. Figure 11 presents a comparison of the beam motion with and without the orbit feedback. When the feedback is off the beam looks already quite stable (less then 1 µm rms), when the feedback is on, the beam motion is further reduced to less then 0.5 µm rms.

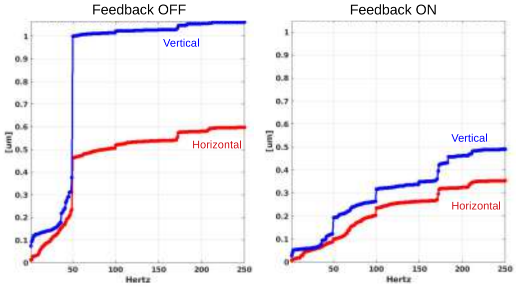


Figure 11: Beam motion with the beam off (left) and on (right) in the horizontal (red) and vertical (blue) plane.

The importance of bunch by bunch feedback became obvious at higher current, where beam instabilities started to arise due to ion trapping. EBS is running from day one of user mode with the same fill pattern of the old machine, most of these fill patterns foresee at least a single bunch filled with high current (from 1 to 8 mA). In order to cope with single bunch instabilities the multi-bunch feedback is operational and reducing blow up effects.

EMITTANCE MONITORS

The emittance monitor of EBS is composed by five pinhole systems taking light from two different source types in order to allow energy spread measurement [11].

Stored Beam

As soon as the beam was stored, the first sychrotron light was observed at the pinholes stations. In order to get an image of the beam at very low current, all filters were removed. The pinhole can be aligned remotely with four degree of freedom. Figure 12 shows the first image of the EBS light. At the time 12 µA of current were present in the storage ring.

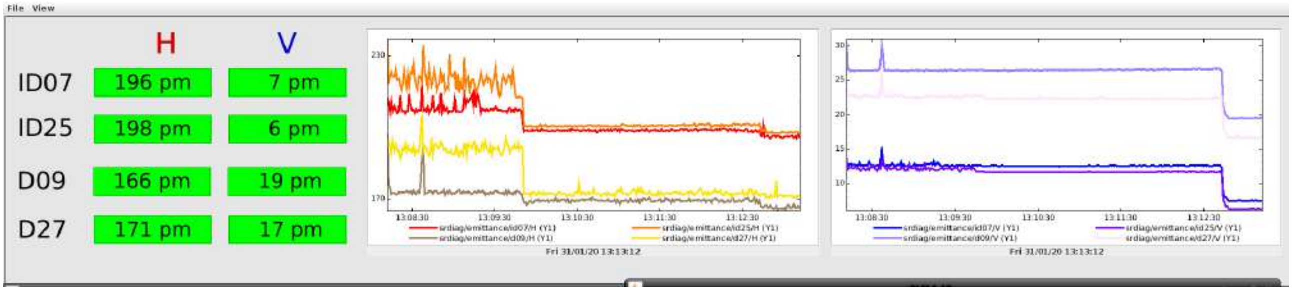
Figure 12: First EBS synchrotron light observed at one of the pinhole locations.

Current Ramp-Up

Once accumulation was achieved, emittance measurements have been used to optimize the machine lattice to achieve the ultimate performances. An example of emittance measurement used during beam optimization is presented in Fig. 13.

OUTLOOK

The role of beam instrumentation in the commissioning of EBS has been primary. All the instruments has been fulfilling all the expectations since day one mainly thanks to the experience gained in commissioning and operating them in the old ESRF machine. This experiences and a



	H	V
ID07	196 pm	7 pm
ID25	198 pm	6 pm
D09	166 pm	19 pm
D27	171 pm	17 pm

Figure 13: Emittance evolution when tuning quadrupoles.

deep knowledge of the equipment have also permitted a non-conventional use for many of them allowing to speed up the full commissioning process.

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