ISBN: 978-3-95450-241-7 ISSN: 2673-5350 doi:10.18429/JACoW-IBIC2022-MOP35

NEW MEASUREMENTS USING LIBERA-SPARK ELECTRONICS AT ESRF: THE HIGH-QUALITY PHASE-MONITOR AND THE SINGLE-ELECTRON

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Abstract

Several new diagnostics have been installed and exploited at the ESRF's new Extremely Brilliant Source (EBS) at the end 2021. A Libera-Spark BPM device has been implemented to measure the phase of Booster and EBS rings, with high resolution and up to turn-by-turn rate. In the Storage Ring we achieved irrefutably the control, injection and measurement of single electron(s) with the use of transfer-line screens, the visible-light extraction system and a low-cost photo-multiplier tube, combined with the commercial Spark Beam Loss Monitor. Further planned developments, like the TCPC technique, on this are on-going and will be essential to verify that our Booster cleaning process reaches a level of zero-electron bunch pollution in EBS.

INTRODUCTION

The Extremely Brilliant Source (EBS) ring is a fourth-generation machine that generates X-rays with a 6-GeV and 200-mA electron beam. The complex chain includes a Linac, a Booster and the EBS ring and it is operational since 2020 at the European Synchrotron Radiation Facility (ESRF) in Grenoble [1].

A large number of diagnostics were used to commission the ring and these devices continue their operation and use for both the User-mode operation (USM) and for studies during the Machine Dedicated Time (MDT) [2, 3].

New diagnostics were implemented recently that exploit to the full the Libera electronics: a beam-phase-monitoring for both the Booster and EBS rings with a Spark-BPM and a single-electron measurement with a Libera Beam Loss Monitor (BLM) [4].

THE PHASE-MONITOR

The measurement of the beam phases of both the Booster and EBS is done by a single Libera Spark, the same model used for the BPMs. With beam phase is defined here the phase relation w.r.t. the ESRF's RF-master source, which is the reference for all cases and results reported here below. This master source is at the heart of both the RF-accelerator system and the distribution of timing signals used for numerous purposes in the ESRF facility.

The principle of using a Spark BPM is similar to a former version that used a Libera-Brilliance-BPM [4]. It uses the so-called I and Q digital signals that are generated on each of the 4 RF input signals. It important to stress that neither the Spark's under-sampling of the rf-frequency (352.2 MHz), nor the internal PLL being a simple software version (quasi-PLL) and therefor wobbly w.r.t. to any external signal to such Spark, does not affect its potential for measuring with high resolution and precision the phase relation between the 4 RF-inputs.

Figure 1 shows the connections of the timing signals and the 4 RF inputs: a) the Booster signal coming from a stripline, b) the EBS-SR signal coming from BPM buttons, and the c) and d) fed by the RF-master-source. For the latter, having 2 identical signals at 2 different inputs allows to assess the resolution of the device.

With an upgraded firmware the Spark now generates directly the phase relations between the 4 RF signal in the SA-stream of 20 Hz.

The I and Q data also being available from triggered buffers, with the turn-by-turn as the fastest rate (355 kHz), also means that the phase information is fully available for studying very fast events.

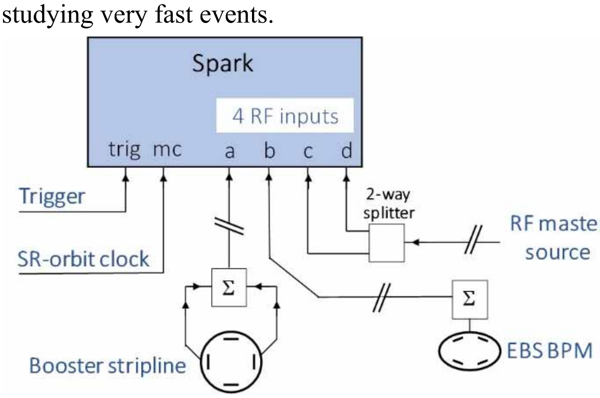

Figure 1: The connections of the phase-monitor.

The Phase Measurement Results, Slow and Fast

The slow (20 Hz) output of the phase monitor is shown in Fig. 2 which shows the phase of the beam under two distinct conditions: the (digital) phase-control-loop in the RF-transmitter system being ON and OFF. This control loop has a (slight) digitization problem that explains the noisy behaviour in the left part of the graph.

The typical resolution with this 20 Hz stream is a few millidegrees.

The device also provides the phase data at the faster rates of 355 kHz and 5.5 kHz (i.e. 2.8 µs and 180 µs sampling time) through triggered buffers. This allows to measure precisely at the injection time and results of this are shown in Figs. 3 and 4.

The green curves in these graphs show the real phase resolution of this measurement monitor, since measured by the device at 2 dedicated channels and in exactly the same manner and at the same time.

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11th Int. Beam Instrum. Conf. IBIC2022, Kraków, Poland JACoW Publishing
ISBN: 978-3-95450-241-7 ISSN: 2673-5350 doi:10.18429/JACoW-IBIC2022-MOP35

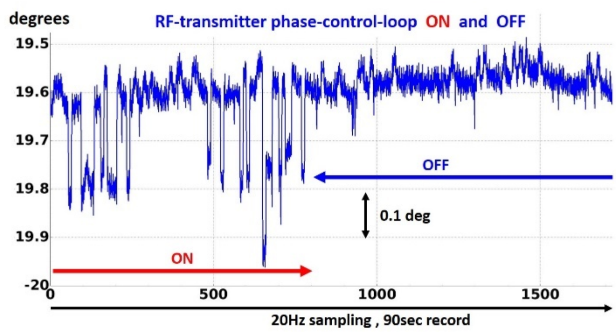

Figure 2: Typical results of the slow phase monitoring.

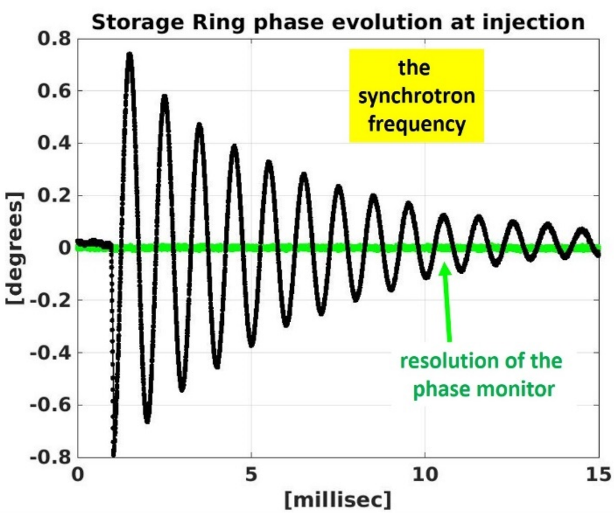

Figure 3: The time-resolved phase at injection.

This data reveals in great details the synchrotron frequency and also the details of our (new) injection scheme with a bump that now starts 50 µs before the injection moment.

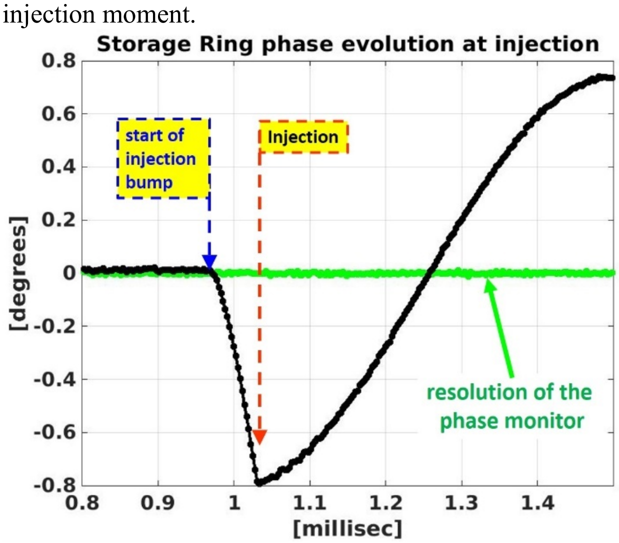

Figure 4: Details of time-resolved phase at injection.

The phase oscillation visible in the time-domain is dominated by the synchrotron frequency. Calculating the frequency spectrum of this yields the red curve shown in Fig. 5.

The exact value of this synchrotron frequency is thus easily and accurately obtained, and it can be measured in dedicated accelerator studies, e.g. as function of the stored beam current, or under different configurations of the RF-cavities. The measurement results of this, together with simulated data is shown in Fig. 6.

To be noted on the black curve in Fig. 5, that is taken a normal decay time, are the spikes at e.g. 100, 150, 300, 600 Hz. These are caused by deficiencies in the power-supply system of some RF klystrons.

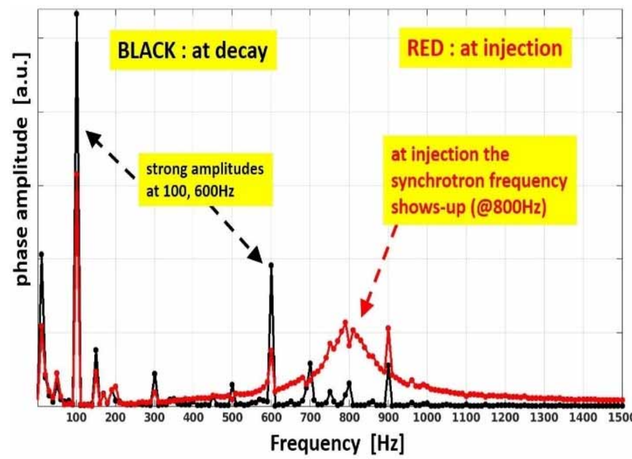

Figure 5: Frequency spectra of the phase, both at injection (red) and during normal decay (black).

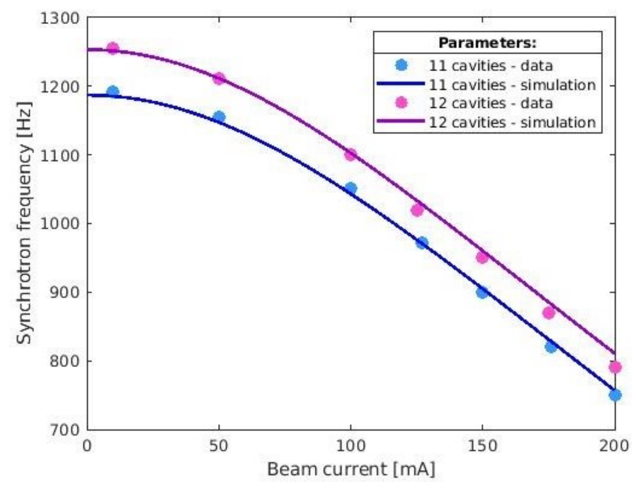

Figure 6: Simulation and measurement results of the synchrotron frequency as a function of beam current.

The Booster Phase Measurement

The same and unique device measures also the time resolved phase of the booster. The 4 Hz Booster has a full cycle of 250 ms, with 135 ms of beam and acceleration time. In Fig. 7 we can observe the high reproducibility of 4 of such consecutive cycles, which shows a swing of about 15 degrees in the middle of the acceleration cycle. These data were taken with 5.5 kHz sampling rate.

In Fig. 8 the details of this are shown, with an oscillatory burst between 80-90 ms after injection. The sampling rate of the monitor here was 355 kHz and this allows to assess that phase oscillation itself with high precision at 13 kHz frequency and 0.5 deg. rms amplitude.

ISBN: 978-3-95450-241-7 ISSN: 2673-5350 doi:10.18429/JACoW-IBIC2022-MOP35

These details are in most cases confirming the theoretical knowledge of the Booster, i.e. the beam dynamics aspects and the functioning of its components like the magnet's ramping power-supplies (RIPS) and the RF-acceleration system.

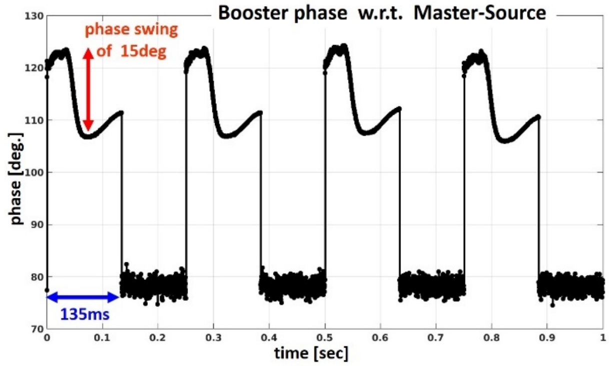

Figure 7: The time-resolved Booster-phase evolution of 4 consecutives injection cycles.

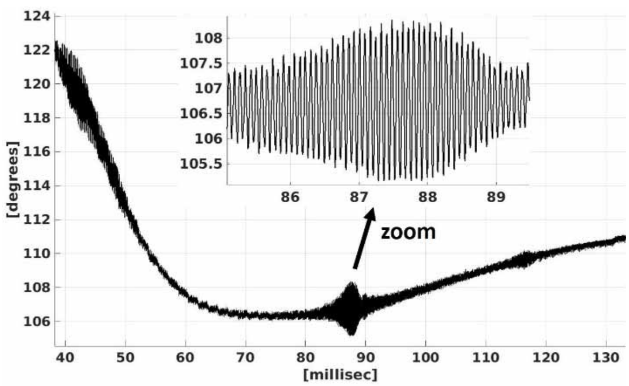

Figure 8: Fine details of the time-resolved Booster-phase.

THE SINGLE-ELECTRON MEASUREMENT

A Libera Beam Loss Monitor (BLM) is used together with a low-cost photomultiplier tube (PMT) and the visible light available in our optics lab for measuring irrefutably a single electron in our EBS storage ring.

The EBS ring has an orbit revolution time of 2.816 µs and it operates with typically 200 mA beam current, which is equivalent to $3.5 \cdot 10^{12}$ electrons. The challenge is considerable to measure the lowest possible beam current which by definition is a single electron. This is obviously far out of range for ordinary current measurement devices.

However, the photon flux produced by synchrotron radiation is huge. This for modern synchrotron light sources in general, and in the visible light spectrum.

The Visible Light Set-Up

In our optics laboratory we have an easy and permanent access to such visible synchrotron light, that is extracted by a system that avoids any major wave-front deformation [5].

The visible light is generated by a 0.62 Tesla dipole magnet and extracted by an in-vacuum water-cooled visible-light mirror that can be completely inserted for low beam currents. That visible light, with roughly 2 mrad of angular divergence extracted in both planes, follows a path through a periscope with 3 mirrors in air, and is conveniently focussed by an achromat (f=3m) onto a compact PMT (model: Hamamatsu 10721-110). The PMT signal is acquired by one channel of the BLM electronics, in integration mode.

The gain of the PMT and the acquisition parameters can be very conveniently controlled by the BLM and thus optimized for this ultra-low level of light detection. In this configuration it can be calculated that, for one single electron stored, the PMT is exposed to about 1500 photons/second, in the 400-700 nm wavelength range.

The Injection and Control of Single Electrons

The production of single electrons in the storage ring is done by operating the injector in a very particular way that is described here below. The injector is comprised of a 200 MeV Linac, a 6 GeV booster synchrotron and 2 transfer-lines. For normal injection this injector delivers about 10^9 electrons at each injection shot, that is working at 4 Hz rate.

For this experiment we need to reduce that to a rate of 1 electron for only every 1000 injections, i.e. 1 electron every 4 minutes. It is to be noted that the above mentioned PMT is a 400 Euros device that is operated in a very ordinary manner, e.g. no cooling etc. Consequently, the noise of this detector is far from ideal and well above the level of 1500 photons/sec. To overcome this, we conveniently operate the BLM with an integration time of several seconds. However, it implies that we need to reduce that single electron injection rate to something significantly slower than that.

This is achieved by operating the our Linac with its gun simply off. In theory this should then never produce any electron at all. However, there is a very small current caused by electrons extracted by the strong electric fields in the Linac acceleration structure. A tiny fraction of these 'parasitic' or 'dark-current' electrons get through into the booster and are then accelerated, extracted and injected into the storage ring. The number of these electrons has been assessed with our device at about 100 electrons per shot. This is still far too much, and in order to reduce this further we use screen monitors in the transfer-line TL2 that simply act like attenuators. The electrons at 6 GeV are not totally affected by these thin screens, and by inserting typically three of such screens we can reduce the injection rate to something like 5 electrons per hour [6].

The Measurement of Single Electrons

The first measurements have been performed in February 2022. The injection chain was continuously injecting at 4 Hz, with Linac gun off, and four TL2-screens were inserted. The PMT was set to 1 MΩ impedance and to 0.7 V gain, and the BLM in integrating mode, with 8-second integration/sampling time to maximize the signal-to-noise ratio.

Figure 9 shows the signal collected over one hour. The five distinctive steps clearly correspond each to the arrival

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of an additional electron. Obviously, in the above described method the arrival time of these electrons is subjected to the intrinsic statistical uncertainties and thus totally unpredictable. Some electrons arrived after 4 minutes, some after 15, in this shown record.

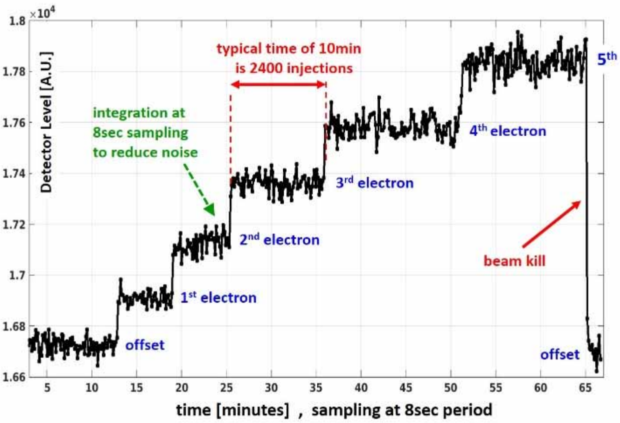

Figure 9: The injection of 1-2-3-4-5 electrons over a time span of 1 hour, measured with 8 sec integration mode.

After one hour we killed the five stored electrons and retrieved the same background level, so temperature effects do not affect this measurement.

The Measurement of Those Undesired Electrons

The above described single-electron set-up has served for some very stringent verifications on the beam filling pattern in the ring. The ESRF has in total 992 RF-buckets for the electrons, but in some particular filling patterns only a few of these are filled (e.g. 16-bunch mode) while all the other buckets should be totally empty.

The above system is limited since it cannot measure if undesired electrons are occupying those buckets that should be empty, if at the same time the good bunches are filled. However, during specific dedicated accelerator studies, we have been able to use it successfully for: (a) the fine-adjustment of some parameters in our dedicated booster bunch-cleaning system and (b) adapting the parameters of the injector's extraction system, like bump amplitude and H-V coupling value, to avoid any untimely extracted electrons to end-up populating buckets that should remain empty.

The above measurement results were confirmed by special detector methods on a user beamline (ID18) that has independent measurement capabilities of detecting close to zero electron pollution levels. In the near future we intend to implement a Time-Correlated-Photon-Counting system so to obtain more flexibility and usefulness in controlling this purity/pollution issue of these undesired electrons.

CONCLUSION

At ESRF, two new Libera-based electronics have been implemented, to constitute two new diagnostics: (1) high performance beam phase measurements with a Spark BPM, and (2) to irrefutably measure beam currents as low as single-electrons using a Spark BLM.

This simple and low-cost high-quality phase-monitor is in permanent operation and very powerful in detecting and studying the slightest phase events, of both slow and fast nature, of the beam in the EBS storage ring.

It has the same functionality and performance for the beam in the Booster.

Extending our capability of beam current measurement down to the challenging single-electron level was successful and has already proven to be useful for some cross-check verifications on the purity issue, which itself is essential for certain specific ESRF user operation modes.

ACKNOWLEDGMENTS

The authors would like to thank the ACU group for the software applications, the Beam-Dynamics and Operation groups for the support during MDT time. Many thanks to the ID18 beamline colleagues for cross-checking the purity levels before and after optimizations.

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